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March 1993

Fort Peck Tunnel No. 1 Rehabilitation, Fort Peck Dam, Montana

by Charles H. Tate, Jr., Richard G. McGee
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Approved For Public Release; Distribution Is Unlimited

Prepared for U.S. Army Engineer District, Omaha

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3909 Halls Ferry Road
Vicksburg, MS 39180-6199

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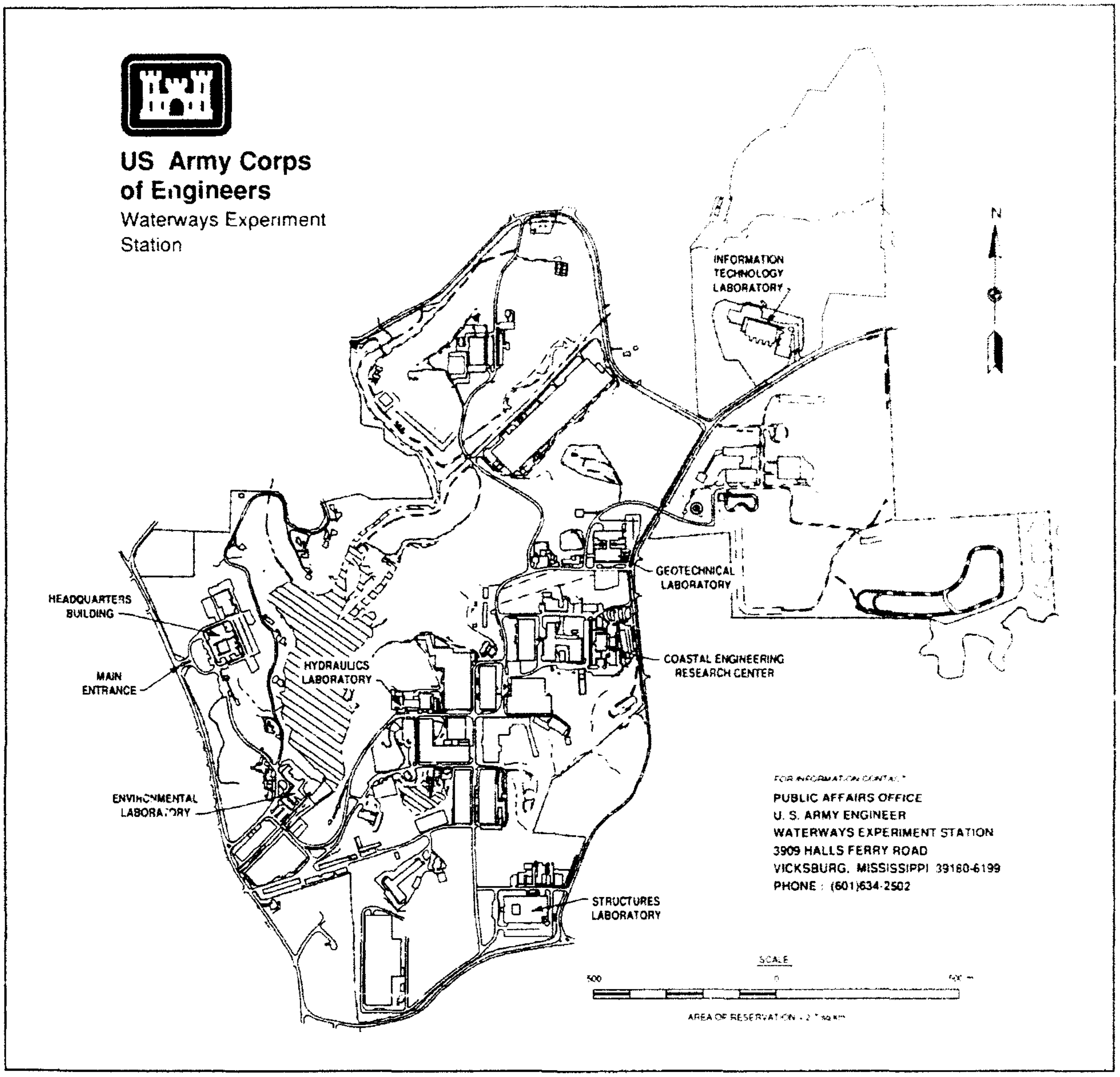

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Contents

Preface

The model investigation reported herein was authorized by Headquarters, U.S Army Corps of Engineers, on 13 July 1989, at the request of the U.S. Army Engineer District, Omaha. The studies were conducted by personnel of the Hydraulics Laboratory (HL), U.S. Army Engineer Waterways Experiment Station (WES), during the period July 1989 to March 1991. All studies were conducted under the direction of Messrs. F. A. Herrmann, Jr., Director, HL, and G. A. Pickering, Chief of the Hydraulic Structures Division, HL. Tests were conducted by Messrs. C. H. Tate, Jr., V. Stewart, and J. Cessna of the Locks and Conduits Branch, HL, and R. G. McGee and M. T. Hebler of the Hydraulic Analysis Branch, HL. Work was conducted under the supervision of Mr. J. F. George, Chief of the Locks and Conduits Branch and Mr. B. J. Brown, Chief of the Hydraulic Analysis Branch.

The model was constructed by Messrs. Edward A. Case, Joseph M. Lyons, and Mitchell A. Simmons of the WES Engineering and Construction Services Division (E&CSD). The model was constructed under the supervision of Mr. Sidney J. Leist, Chief of the Model Shop, E&CSD, and Mr. Mickey L. Blackmon of the Machine Shop, E&CSD, under the supervision of Mr. Patrick Crumm, Chief of the Machine Shop, E&CSD. Instrumentation support was provided by Mr. S. W. Guy, under the supervision of Mr. L. M. Duke, Chief of the Operations Branch, Instrumentation Services Division, WES. This report was prepared by Messrs. Tate and McGee.

Messrs. Gerus M. Rubingh, Don Sachs, Tom Scott, Craig Margrave, Rick Guziec, Bill Doan, Roger Kay, Craig L. Chapman, Tim Temeyer, and Bob Buchholz of the Omaha District, and Messrs. Warren Mellema, Ron Bockerman, Albert R. Swoboba, Tom Pfeffer, and Joseph M. Pletka of the U.S. Army Engineer Division, Missouri River, visited WES during the course of the model study to observe model operation and correlate results with concurrent design works.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Leonard G. Hassell, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
inches	25.4	millimeters
miles (US statute)	1.609347	kilometers
pounds (force) per square inch	6.894757	kilopascals

1 Introduction

Fort Peck Dam and Lake is located on the Missouri River 18 miles[1] southeast of Glasgow, MT (Figure 1), and is one of the oldest and largest hydraulic earth fill dams in the world. The project was initially designed with four tunnels to release flow from the lake and two of the tunnels have had powerhouses with multiple turbines installed at the downstream end of the tunnel. Fort Peck Powerhouse No. 1 was put into operation in 1943 and some of the components now need replacement or repair. Replacement of a short free-standing segment of the tunnel downstream of the buried tunnel, the plug funnel trifurcation, and the three penstocks leading to the turbines at Fort Peck Powerhouse No. 1, has been proposed by the US Army Engineer District, Omaha, for several years. This is because their factors of safety have been determined to be inadequate due to the lack of expansion/contraction joints in the penstocks, welding performed on the riveted joints, and increased penstock surge pressures that will result from increased surge tank riser restrictions that are needed to prevent surge tank overtopping. A review of pertinent literature (Rao et al. 1969)[2] by the Omaha District indicated that a Sulzer Escher Wyss (SEW) trifurcation would be significantly more efficient and could result in additional power revenues if the SEW design was used to replace the existing plug funnel trifurcation. The Omaha District identified additional ways to reduce the energy loss through the conduit. One possible location to reduce the energy loss was determined to be the opening to the control shaft surge tank that, prior to the construction of the powerhouse, was originally designed to house a ring gate.

A physical model study of the proposed SEW trifurcation was recommended to verify the published loss characteristics (Rao et al., op. cit.) and to ensure that unstable flow conditions were not introduced into the scroll cases of the existing turbines. A second physical model was used to quantify the energy losses through the control section, and determine possible modifications that would further reduce these losses.

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[1] A table of factors for converting non-SI units of measurement to SI units is presented on page v.

[2] Rao, Palepu V., Misra, H. C., Juyal, R. V., and Sharma, S. N. P. (1969). "Hydraulic performance of penstock trifurcations," *Journal of the Power Division, Proceedings of the American Society of Civil Engineers* 95, 6456.

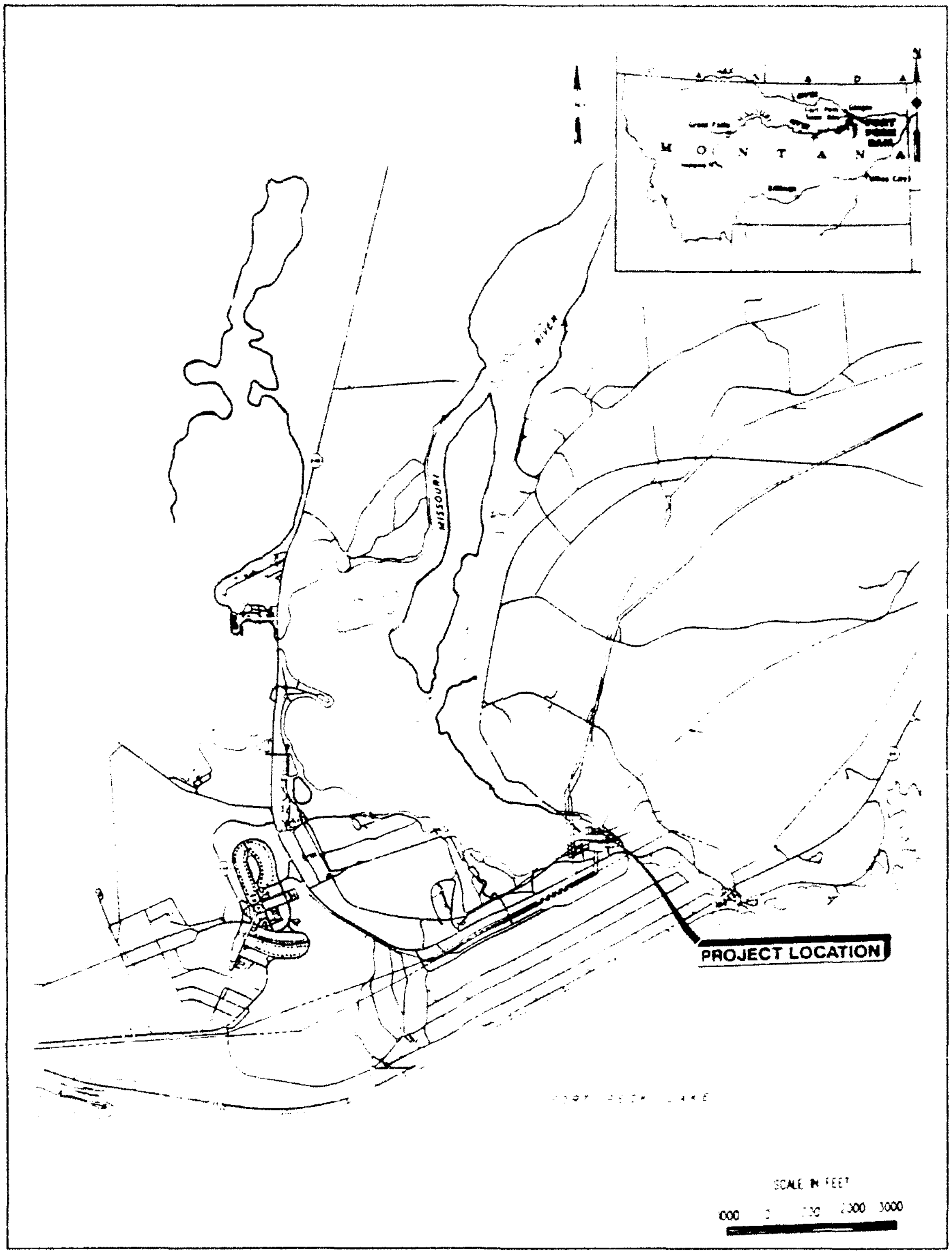


Figure 1. Project location

2 The Models

Description

Two physical models were constructed at a 1:25-scale to consecutively study the proposed SEW trifurcation and the control section that included the emergency gate slots and the opening to the control shaft surge tank. Both models were constructed of acrylic plastic and used the same sections of conduit, where possible. The same head tank and weir box were used for both models with some modifications to the weir box.

The model used to study the proposed SEW trifurcation reproduced approximately 1,300 ft of conduit upstream from the trifurcation, including the long radius curve, and the trifurcation to a point approximately 50 ft downstream of the existing butterfly valves. The model layout is shown in Plate 1 and Photo 1. Wood forms were inserted into the molded tunnel sections during assembly to ensure smooth joints. The SEW trifurcation was composed of 14 conic sections of which all but three were machined from large blocks of acrylic plastic (Plate 2 and Photos 2-4). The remaining three sections were molded on machined molds due to the size of the sections. The crotch plates were machined of aluminum for durability and in anticipation of attaching strain gages, if necessary. The riser orifices, the surge tanks, the crossover pipes between the surge tanks, and the butterfly valves were not installed in the model during initial construction to simplify testing of loss conditions in the trifurcation.

Flow to this model was supplied through a circulating system. Discharges were measured by a sonic flowmeter and v-notch weirs. Discharges were controlled with slide gates at the ends of the penstocks. Several types of control gates were used during the study to determine if the type of gate had any effect on the model performance. No differences were noticed, so the simple slide gate was used for the majority of the model operation. Visual indications of the flow conditions through the trifurcation were obtained by injecting dye into the model through the piezometer taps and bleed lines.

The control section model consisted of the transition from the 24-ft, 8-in.-diam conduit to the throat section, the throat section (which contained gate slots for two emergency gates and a center pier), the transition from the throat

section back to the circular conduit, and the control shaft surge tank orifice (Plate 3). Approximately 1,000 ft (prototype) of straight circular conduit was installed upstream and downstream of the control section (Photo 5).

Flow to this model was supplied through a circulating system. Discharges were measured utilizing a v-notch weir and were controlled with a gate valve on the inflow line to the head tank. Another gate valve was used at the downstream end of the model to control the total head on the model. Visual indications of the flow conditions through the control section were obtained by injecting dye into the model through the piezometer taps, special injection ports, and bleed lines.

Similitude

The accepted equations of hydraulic similitude, based on the Froudian criteria, were used to express mathematical relations between the dimensions and hydraulic quantities of the model and prototype. General relations for the transference of model data to prototype equivalents are listed in the following tabulation. Model measurements of discharge, water-surface elevations, and velocities can be transferred quantitatively to prototype equivalents by means of the scale relations.

Characteristic	Dimensions[1]	Scale Relations Model:Prototype
Length	L_r	1:25
Area	$A_r = L_r^2$	1:625
Velocity	$V_r = L_r^{1/2}$	1:5
Discharge	$Q_r = L_r^{5/2}$	1:3,125
Volume	$V_r = L_r^3$	1:15,625
Time	$T_r = L_r^{1/2}$	1:5

[1] Dimensions are in terms of length.

No attempt was made to reproduce full dynamic similitude in either model; however, the effects of reduced Reynolds numbers (R_n) during model operations were investigated. Froudian scale relations do not require a free surface to be valid for hydraulic models. A very good explanation on applying Froude criteria to pipe flow situations can be found in *Hydraulic Modeling* by J. J. Sharp.[1] The main criterion is that R_n be large enough to result in a constant loss relation. This is usually accomplished by operating the model over a

[1] Sharp, J. J. (1981). *Hydraulic Modeling*. Butterworths, London.

range of R_n to determine the limiting value below which the loss relation may not be constant. The U.S. Army Engineer Waterways Experiment Station (WES) model was operated in this manner, the observed loss values were fitted to the theoretical form, and the residuals were analyzed for systematic variations associated with low R_n. Based on this analysis, the limiting R_n was associated with a prototype discharge of 1,950 cfs in the 24.67-ft-diam tunnel. Loss coefficients for the proposed trifurcation were determined from discharges greater than 1,950 cfs only.

Measurements and Equipment

Locations of the test instrumentation are shown in Plates 1-3. Information on each piezometer and transducer is listed in Tables 1 and 2. The following paragraphs describe the different types of measurements and their respective instrumentation.

Hydraulic Grade Lines

General

Preliminary guidance concerning expected energy losses (0.5 ft or less, prototype) for the trifurcation model dictated the use of elaborate data acquisition techniques. By using differential piezometry from station to station, coupled with highly sensitive differential pressure transducers, piezometric head loss was directly measured with excellent resolution. By summing these individual differential measurements, the hydraulic grade line for the Fort Peck system was generated. Plate 4 is a schematic of the piezometric layout and transducer manifold.

Power tunnel

For this discussion, the power tunnel extends from the head tank at model sta 00+00 to the upstream trifurcation piezometer ring (No. 4) at sta 13+81. Plate 1 shows the piezometer locations. The piezometers for the power tunnel were located to measure losses related mostly to form (i.e., entrance, curves, deflections, etc.). Piezometer No. 0 measured the head elevation in the head tank and was the reference pressure. Piezometer No. 1 was at sta 02+44 at the upstream end of the curve and piezometer No. 2 was at the downstream end (sta 07+65). Piezometer No. 3 was located just upstream of the first horizontal deflection approaching the trifurcation at approximately sta 12+98. A differential measurement between piezometer Nos. 0 and 4 was provided as a check of the head loss summations through the power tunnel. In addition to the differential measurements between piezometer stations, absolute measurements using appropriate pressure transducers were provided for each piezometer (refer to Table 3 for transducer descriptions).

Trifurcation

Photo 3 and Plate 2 show the trifurcation instrumentation plan. Piezometer ring No. 4 (TPU), located immediately upstream of the trifurcation, was the reference pressure for the loss measurements across each leg of the trifurcation. The head loss was determined by differential measurements between piezometer No. 4 and piezometers 5 (TPR), 6 (TPC), and 7 (TPL), for the No. 1, 2, and 3 penstocks, respectively. These locations are approximately 4-5 ft (prototype) downstream of the trifurcation at sta 14+48.

Penstocks

The last set of piezometer rings were installed on the penstocks at locations just upstream of the penstock surge tank locations (surge tanks not installed on model). These locations are approximately 10 diameters upstream of the model flow control gates and were so placed to prevent disturbances to the pressure readings due to the exit conditions. The reference pressures for the penstock loss measurements were piezometers 5, 6, and 7, and the downstream measurements were from piezometers 8, 10, and 12 for the No. 1, 2, and 3 penstocks, respectively.

Piezometer rings

Piezometer rings were used to obtain the best average of the piezometric pressure along the center line of each flow passage. The rings consisted of four 1/8-in. drilled piezometer holes interconnected with 1/4-in. pressure tubing for averaging. A piezometer line was run from the top of each ring to the transducer manifold board. The relatively large diameter of the piezometer lines, coupled with the long line lengths, ensured adequate damping of most higher frequency fluctuations, which are of no concern in measurement of the average head loss.

Differential pressure transducers

Differential pressures were measured between each piezometer ring location, as shown in the piezometer schematic (Plate 4). A 0.125-psid differential pressure transducer was used between each ring.

The differential transducers were calibrated in the laboratory utilizing a precision variable water level device with an accuracy of 0.001 ft. Three series of laboratory calibrations were conducted prior to testing, and two sets of on-line calibrations were performed during testing to monitor possible drift in the electronics. All gages were checked for linearity and calibrated to 100 percent over range. The result of these calibrations was a worst-case error of less than 0.25 percent of full scale. Using a conservative value for transducer resolution of ± 1.0 percent of calibration full scale, the resolution

was 0.0014 ft (0.035-ft prototype) for the tunnel measurements and 0.0029 ft (0.0072-ft prototype) for the trifurcation.

Trifurcation pressure fluctuations

Due to the Fort Peck layout, specifically, the two distinct power tunnel deflections just upstream of the trifurcation, the decision was made to monitor pressure fluctuations at perceived critical locations in the trifurcation. Flush-mount absolute pressure gages were mounted in the vicinity of the trifurcation crotch plate and along the inside wall of each penstock passage. The reader is referred to Plate 2, Photo 6, and Table 2 for actual locations.

The gages were miniature semiconductor pressure transducers manufactured by Druck Limited. The gage diaphragms had a diameter of 0.147 in. with a 5-psi pressure range. The gages were calibrated with a precision dead-weight tester to an accuracy of 0.1 percent full scale.

Data acquisition

The data from all transducers were collected simultaneously using digital data acquisition equipment. This data acquisition and reduction system, dubbed the DARS, is a Masscomp Model MC5500 computer capable of digitizing 64 channels of data simultaneously at an aggregate sampling rate of approximately 800,000 samples/sec (s/s). Twenty-four channels of data were monitored for the Fort Peck model tests. The data statistics (i.e., mean, maximum, minimum, and standard deviation) were generated immediately post-test, as were time history plots for verification of the data.

All data channels were sampled at a rate of 100 s/s for the head loss evaluations. For tests concerned with pressure fluctuations only, the rate was increased to 500 s/s. This high rate was chosen to ensure proper scaling between the model tests and possible prototype tests.

Test Procedures

Test scenarios followed those shown in Table 3. All testing was performed under steady-state conditions. Repeatability is an important factor in establishing confidence in the data. Therefore, three levels of repeatability had to be met before a test series was considered complete. The first level was test to test. A 1-min test was conducted for each condition and repeated a minimum of three times. The head loss for a particular discharge was then computed as the mean of three (or more) tests. Second, the data had to be repeatable from day to day. A 50-percent overlap for each test scenario was assured. This provided for one half of the data in a test case to be repeated. And finally, the data had to be repeatable from calibration to calibration. These data were

spot-checked after on-line and post calibrations were performed on the transducers to monitor the effects of electrical drift or zero shifts.

Discharge was measured directly with v-notch weirs located at the downstream end of the model. The flow measurement had the largest error range of ±3 percent, which equates to approximately an error range of ±6 percent for the loss coefficient K. The discharge values were compared with head loss measurements at both the entrance and across the trifurcation to obtain the relationship between the theoretical and the experimental. That is, head loss is proportional to the square of the discharge. This theoretical relationship was maintained for all flows at the entrance and across the trifurcation for single penstock operations.

Initial model tests were conducted with penstock 2 operating at various flows. A statistical analysis of the curve fitting of the trifurcation differential pressure indicated a possible R_n effect for discharges below 1,950 cfs (prototype). Consequently, future model tests were limited to flows greater than 1,950 cfs except for a few lower flows that were used to indicate the magnitude of possible variations in the loss coefficient due to the R_n.

3 Tests and Analysis

Trifurcation Model

Model testing

The Omaha District based the decision to use the SEW trifurcation on values found in relevant literature[1] and an economic analysis spreadsheet that included five flow distribution scenarios that were time weighted. The model was tested in a manner to develop the loss characteristics for the five scenarios listed in Table 3 where the maximum discharge through units 1 and 3 was 3,950 cfs and the maximum discharge through unit 2 (center unit) was 1,650 cfs. Two additional flow scenarios were added to the study based on the anticipated future condition that the center turbine would be upgraded to the same size as the other two units. These conditions were with equal flow in all penstocks with 2,900 and 3,950 cfs per penstock.

For comparison with the Omaha District spreadsheet, the same analysis methodology and equations were used to analyze the model results. Due to the branching nature of the flow analysis and the unequal energy distribution forced on the trifurcation system, some of the analysis methodology was not rigidly applicable to this situation, but was used for comparison purposes. Bernoulli's Energy Equation was used to compare the energy levels at points immediately upstream and downstream of the trifurcation for each penstock. The differences in the energy and hydraulic grade lines were used to determine the energy loss between the two points. Due to the difficulty of setting an exact flow combination in the model, the model was operated by stepping through flows over the operation range. For the range of flows tested in each operation scenario, a multiplicative coefficient K of the upstream velocity head was computed and the product was equated to the energy loss through the trifurcation for that penstock. This relation is shown in the equation

[1] Rao et al., op. cit. p. 1.

$$H_L = K \frac{V^2}{2g}$$

where

H_L = energy loss, ft of water

K = loss coefficient

V = flow velocity, ft/sec

g = gravitational constant, 32.17 ft/sec/sec

Typical time histories for the differential pressures measured across operating legs of the trifurcation for flow combinations similar to the specific test cases listed in Table 3 are presented in Plates 5-7. A visual inspection of the piezometric time histories seems to indicate that the level of turbulence at the downstream trifurcation piezometer taps varies from case to case. For single operations (Plate 5) there is little difference, all the data being "quiet," so to speak, although the outboard penstocks indicate more turbulence than the center, as expected. However, for the triple operation, test case No. 2 (Plate 7), turbulence in penstock 1 is quite pronounced compared to that in penstocks 2 and 3. Also, for penstock 3, an intermittent, yet consistent, low-frequency fluctuation was detected at piezometer No. 8. Visual tests using dye verified the data. Some flow separation seems to occur within the trifurcation in the vicinity of penstock 3. The fluctuation, presented in Plate 7, occurred due to shedding off the region of flow separation.

Hydraulic and energy grade lines for each test case are presented in Plates 8-14. A relatively large loss is shown as occurring between the head tank and piezometer 1. This loss is not constant throughout this section as the grade line plots infer; rather, most of the loss results from the entrance. The loss in the approximately 220-ft straight tunnel section upstream of the curve should be assumed to slope according to piezometers 2 and 3.

The section of conduit between piezometers 1 and 2 is a long radius curve and the section between piezometers 2 and 3 is an approximately equivalent length of straight tunnel section. Because of the long curve length and large tunnel diameter, coupled with relatively low velocities, the change in loss expected for these sections is minimal, and smaller than the model measurement capability.

The section of conduit between piezometers 3 and 4, which includes the two horizontal deflections, also shows little or no change in slope of the grade line relative to sections 1 and 2 and 2 and 3. The loss for this section (for most tests) is below the range of the measurement system due to the very short distance between taps (83-ft prototype), the large diameter, and relatively low

velocities. Therefore, greater probability of error exists in this measurement. This error is insignificant in relation to the loss through the entire Fort Peck system.

As expected, most of the loss occurs through the trifurcation. The amount of loss through each leg is a function of the flow conditions entering the trifurcation and the established operating conditions. The apparent gain in energy for the center penstock during triple operations is not an error in measurement and is discussed later.

Loss coefficients (K) were computed for single penstock operation by curve fitting the trifurcation differential pressures against the upstream velocity head. The sample correlation coefficient r is used to measure the strength of a linear relationship, with a value of 1 defining perfect correlation.[1] Regressions for the three single penstock operations all resulted in r values greater than 0.99. To determine K's for multiple penstock operations, the head loss for each penstock was computed and these values fitted against the upstream velocity head to determine K. However, several scenarios indicated strong nonlinear energy loss relations. These situations appear to be related to the varying ratio of flows when the flow through one penstock is being held relatively constant and to the flow nonsymmetry caused by the two bends located immediately upstream of the trifurcation. The nonsymmetry of the flow entering the trifurcation appears to be related to the differences in loss characteristics between penstocks 1 and 3. Table 4 shows some of the K's used by the Omaha District in their initial economic analysis.[2] The K values used for the initial economic evaluation of the SEW trifurcation were supplied by Sulzer and are listed in parentheses in Table 5. Model K values for the spreadsheet scenarios and some other flow combinations are shown in Table 5, which is arranged similar to Table 4 for comparison. It should be noted that the literature values shown in Table 4 are for equal flow conditions in the various legs of the subject trifurcation and that this usually results in the lowest loss values. The values shown for this study often are for unequal flow conditions and could be expected to be greater than the values for equal flow splits. The Sulzer values were determined using a model study with air and ideal entrance and exit conditions and are computed form loss values only. The values shown for the Fort Peck model study represent the trifurcation performance within the Fort Peck system geometry and include all losses between data collection locations.

The maximum flow tested ranged from approximately 3,200 to 4,200 cfs, depending on the measured differential pressure. The differential pressure cell's size was based on information provided by the trifurcation designer. In some cases, the measured differential pressure exceeded the range of the installed equipment. For some of these situations the loss coefficients were determined by projecting outward to the required flows. Due to the occasional nonlinear trends for the unbalanced flow conditions, some of these projections

[1] Miller, Irwin, and Freund, John. (1977). *Probability and Statistics for Engineers*. Prentice-Hall, Inc., Englewood Cliffs, NJ.

[2] Rao et al., op. cit. p. 1.

are questionable. The differential pressures across the trifurcation versus flow (Q) for single penstock operations are shown in Plate 15. These plots relate to cases 4, 5.1, and 5.3 in Table 5. For single penstock operations, the energy loss is a linear relation to the upstream velocity head. In these plots the differential pressure is shown relative to Q to show the effect of increasing Q. For branching flow scenarios, the energy loss coefficient was determined as a linear relation where the relation may have had nonlinear trends. Plots illustrating branching flow scenarios used differential pressure and the upstream velocity head to compare the computed K with the observed data. Plots of head loss versus the upstream velocity head are shown in Plate 16 for cases 3.1 and 3 3, where the flow in penstock 1 or 3 is variable and the flow in penstock 2 is held as close to 1,650 cfs as possible. The energy loss coefficients for those flow scenarios are shown in Table 5. The straight lines in the plots represent the computed K values and indicate the nonlinear nature of the loss characteristics when compared to the plotted data. Plate 17 shows the losses when flow is approximately equal in penstocks 1 and 3 and approximately constant at 1,650 cfs in penstock 2. Negative loss characteristics (Plate 14) shown for penstock 2 are probably due to the nonsymmetry of the flow entering the trifurcation and the higher velocity core of the flow through the trifurcation. These values do not violate laws of nature but simply reflect the analysis methodology and some of its shortcomings. The reader is reminded that the total loss across the trifurcation must be considered. There is a net loss of energy across the model trifurcation made up of large losses in the outboard penstocks and a small to apparently negative loss in the center. The strong nonlinear relation evident for penstock 3 makes energy loss projections for higher flows questionable. Loss characteristics for equal flows in all three penstocks are shown in Plate 18.

Control Section Model

The Omaha District requested energy loss characteristics for four conditions as determined from the 1:25-scale model of the control section of the Fort Peck Conduit No. 1 (Plate 3). The model was tested in a manner similar to the trifurcation model. Analysis was simpler in that Bernoulli's Equation was applicable to this model with one inflow point and one outflow point. The four test conditions were as follows:

a. Case 1 - Gate slots open and orifice open

b. Case 2 - Gate slots filled and orifice filled

c. Case 3 - Gate slots filled and orifice open

d. Case 4 - Gate slots open and orifice filled

Case 1 was the existing condition and Case 2 represented the maximum improvement possible if the basic geometry of the control section was not

changed. Cases 3 and 4 identified the energy loss improvements possible at either the emergency gate slots or the orifice to the control shaft.

Energy losses were measured with differential pressure cells (the same cells used in the trifurcation model) at several locations in the model. The differential across the control section was used to determine the energy loss characteristics for each case listed above. Free-surface piezometers were used as a check on the differential pressure cells. Absolute pressure cells were also used, but the pressure differences between the measurement locations were so small as to be within the measurement accuracy of the absolute pressure cells. Consequently, these results were not used in the energy loss analysis.

The energy loss characteristics for each case are described as a loss coefficient, K, as described on pages 9 and 10. The loss coefficient for each case includes all losses from a point 25 ft upstream of the control section to a point 67 ft downstream of the center line of the orifice to the control shaft surge tank.

The energy loss coefficients for Cases 1 and 2 were 0.53 and 0.36, respectively, as shown in Plate 19. These results indicate that the maximum improvement possible is 0.17 times the velocity head. Plate 20 shows that the loss coefficients for Cases 3 and 4 were 0.36 and 0.52, respectively. This indicates that almost all of the improvement would occur at the emergency gate slots and that modifications to the orifice to the control shaft surge tank would have very little impact on the energy loss in the system.

Observations of dye in the flow indicated significant turbulence at the emergency gate slots and circulation through the control shaft surge tank. The circulation through the surge tank was not of a turbulent nature.

Another test case (Case 5) was developed where a deflector was installed on the upstream side of the emergency gate slot except for the invert. A testing program was conducted in a WES flume to determine the required dimensions for a deflector to cause the flow to jump the 4.5-ft-wide gate slots with velocities ranging between 10-12 fps. The resulting deflector was triangular, 0.25 ft high with a 1V on 12H ramp approaching the gate slot. The loss coefficient for Case 5 was 0.58 (Plate 21). This value is larger than for the case without the ramp due at least in part to the reduced cross-sectional area in the throat section and to the form loss associated with the deflector.

4 Summary, Conclusions, and Recommendations

Summary and Conclusions

The proposed replacement of the trifurcation at Fort Peck Powerhouse No. 1 was based on published energy loss coefficients from which the SEW trifurcation was selected. To ensure acceptable flow conditions through and downstream of the trifurcation and to verify the energy losses through the trifurcation, a physical model study was conducted of that portion of the powerhouse system. A physical model study was also conducted of the control section located upstream from the trifurcation to determine if simple modifications would reduce the energy losses in that area. Both model studies were conducted at 1:25 scales and used differential and absolute pressure measuring devices to determine the energy losses through the models.

The energy losses through the SEW trifurcation, as determined by the model, were larger than expected based on published loss coefficients. This may be due to the published values representing only the analytically determined form loss, while this model study includes all losses through the trifurcation. Deflections in the conduit approaching the trifurcation may disturb the flow and add to the observed losses for the Fort Peck application. The installed design at Fort Peck is slightly different from the modeled design in that the two deflections have been combined as one deflection and the trifurcation was relocated approximately 6 ft upstream. The effects of these differences can not be quantified based on this study, but are not expected to be significant. Despite the higher than expected losses, the SEW trifurcation exhibits low energy losses compared to the published values for other designs, as shown in Tables 4 and 5. Additionally, the SEW trifurcation has significantly lower loss coefficients when operating with uneven flow distributions, which is the expected norm for the Fort Peck installation.

Loss characteristics through the existing control section were determined as were the loss characteristics for three potential modifications. Modifying the opening to the control shaft surge tank would not measurably change the energy loss. Placing deflectors upstream of the emergency gate slots was not effective in reducing the energy loss due to the large deflector required to

cause the flow to "jump" the gate slot. This modification resulted in an increase in energy losses. Filling the gate slots resulted in a significant reduction in energy loss. This modification could be accomplished with a picture frame type of insert that could be lowered into the gate slot.

Recommendations

Based on the results of the model testing, especially in relation to preliminary guidance received from SEW, a thorough prototype investigation is recommended. The testing should focus on two major areas: (1) prototype loss coefficients, and (2) effects of flow conditions on trifurcation performance relative to pressure fluctuations, flow separation, and possible cavitation problems.

Piezometer rings should be installed in the prototype at or near each of the model locations. This will ensure accurate model-prototype correlations as well as provide a good first estimate as to the most desirable locations. Exact locations are best determined after final plans are developed. The WES will provide detailed plans and specifications for the proper installation of piezometer rings at the Omaha District's request.

Table 1
Trifurcation Study Piezometer Locations

Piezometer Code	No.	Location[1]		Type	Measurement
		Section	Station[2]		
PO	0	Head Tank	00+00	Piezometer Tap	Upper Pool EL
P1	1	Curve begin	02+44	Piezometer Ring	Absolute Press.
P2	2	Curve end	07+65		
P3	3	Tunnel	12+98		
TPU	4	Trifurcation	13+81		
TPR	5		14+48 (Penstock 1)		
TPC	6		14+48 (Penstock 2)		
TPL	7		14+48 (Penstock 3)		
SRU	8	Penstocks	15+02 (Penstock 1)		
SCU	10		14+88 (Penstock 2)		
SLU	12		15+00 (Penstock 3)		

[1] See Photo 3, Plate 1, and Plate 4.
[2] Station numbers are referenced to the model.

Table 2
Trifurcation Study Transducer Descriptions

Code	Type	Location No.[1]	Range	Description
Tunnel				
PO	Pressure	0	±5 psi	Absolute Pressure
P1		1		
P2		2		
P3		3		
DPO-1	Diff. Press.	0-1	±0.125 psid	Piezometric Pressure Between Taps
DP1-2		1-2		
DP2-3		2-3		
DP3-4		3-4		
DP1-4		1-4		
Trifurcation				
DP4-5	Diff. Press.	4-5	±0.125 psid	Piezometric Pressure Between Taps
DP4-6		4-6		
DP4-7		4-7		
DP5-8		5-8		
DP6-10		6-10		
DP7-12		7-12		
TFL1	Pressure	Left Crotch[2]	±5 psi	Pressure Fluctuations
TFL2				
TFL3				
TFL4				
TFR1	Pressure	Right Crotch[2]	±5 psi	Pressure Fluctuations
TFR2				
TFR3				
TFR4				

[1] Refer to Encl 2 for locations.
[2] Referenced to downstream direction.

Table 3
Existing Plant Operation Scenarios

Case No.	Unit 1 or 3		Unit 2		Unit 3 or 1		Relative Frequency
	% of Capacity	Flow, cfs	% of Capacity	Flow, cfs	% of capacity	Flow, cfs	
1	100	3,950	100	1,650	100	3,950	10 Percent
2	73	2,900	100	1,650	73	2,900	40
3	73	2,900	100	1,650	0	0	40
4	0	0	100	1,650	0	0	5
5	73	2,900	0	0	0	0	5
6[1]	100	3,950	100	3,950	100	3,950	-
7[1]	73	2,900	73	2,900	73	2,900	-

[1] Upgraded Unit/No. 2; planned but not installed.

Table 4
Comparison of the Energy-Loss Coefficients, K , for Different Types of Trifurcation with Equal Flows in Each Branch

Trifurcation	Three Branches Flowing	Two Branches Flowing	One Branch Flowing
Plug-funnel type I	1.14	2.7	13.7
Plug-funnel type II	0.96	2.8	9.2
Double wye	1.66	2.96	5.15
Trifurcation with tie bar	0.46	0.81	3.51
"Esher Wyss" wyes	0.22	1.27	2.06
U.S.B.R wyes (1)	0.57	1.69	2.76
U.S.B.R. wyes (2)	1.23	2.99	4.90
Abrupt entry	2.01	4.52	17.2

Table 5
Energy Loss Coefficients

Case No.	Unit No.	Q	Three Branches Flowing	Two Branches Flowing	One Branch Flowing
1	1	3950	0.73 (0.11)		
	2	1650	-0.21 (0.00)		
	3	3950	0.40[1] (0.11)		
2	1	2900	0.73 (0.11)		
	2	1650	-0.21 (0.00)		
	3	2900	0.40 (0.11)		
3.1	1	2900		0.63 (0.06)	
	2	1650		0.06 (0.00)	
3.3	2	1650		0.15 (0.00)	
	3	2900		0.91 (0.06)	
4	2	1650			2.02 (0.42)
5.1	1	2900			1.80 (0.50)
5.3	3	2900			1.95 (0.50)
6	1	3950	0.63		
	2	3950	-0.10		
	3	3950	0.24		
7	1	2900	0.63		
	2	2900	-0.10		
	3	2900	0.24		

Note: Numbers in parentheses were supplied by Sulzer Escher Wyss.
[1] Questionable projection.

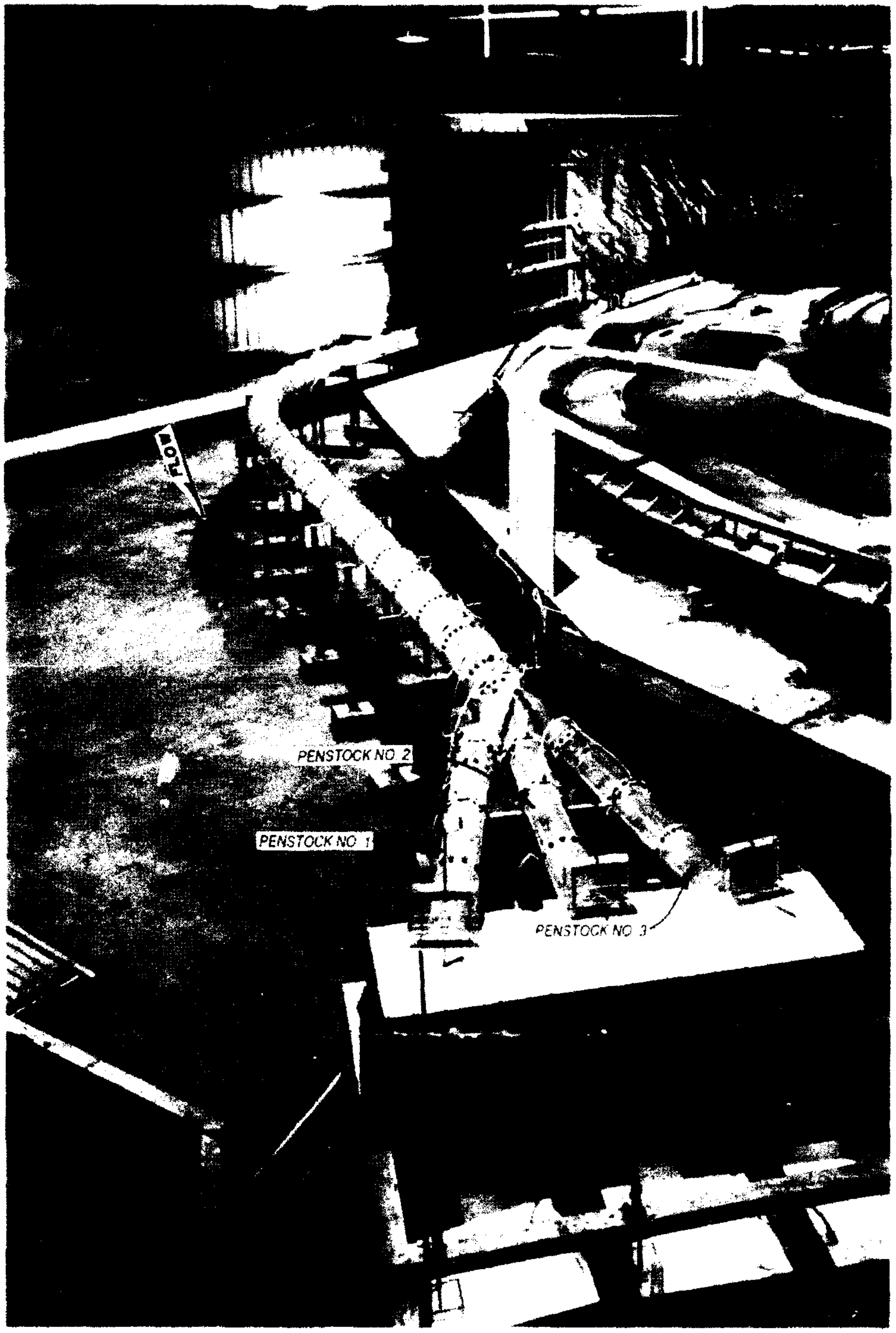


Photo 1. Trifurcation model, looking upstream

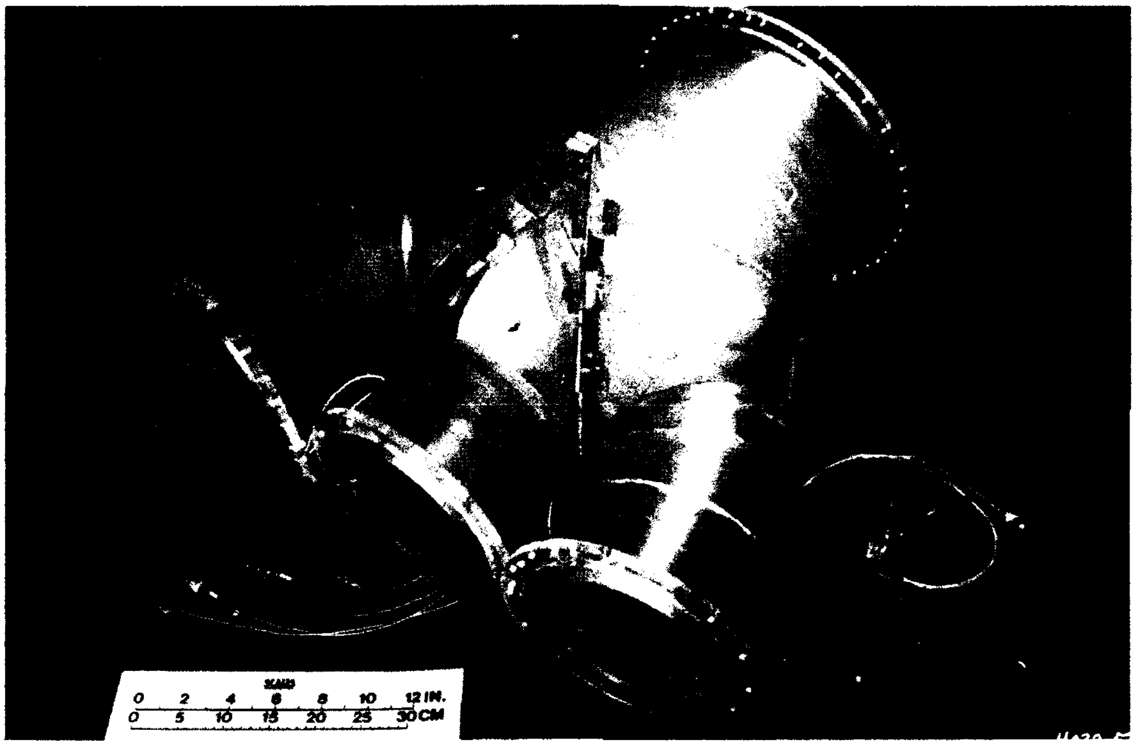


Photo 2. Trifurcation section

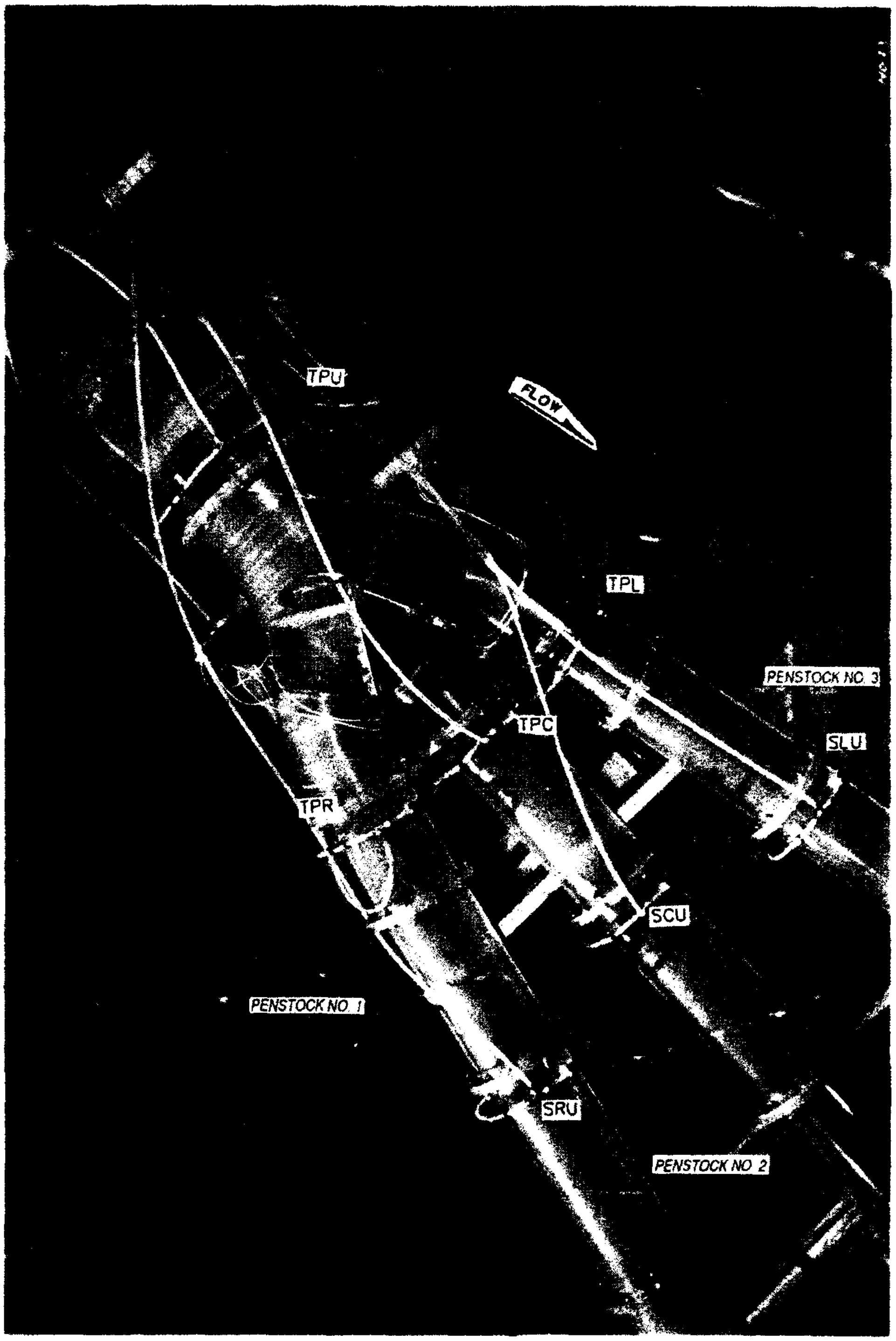


Photo 3. Overhead view of trifurcation

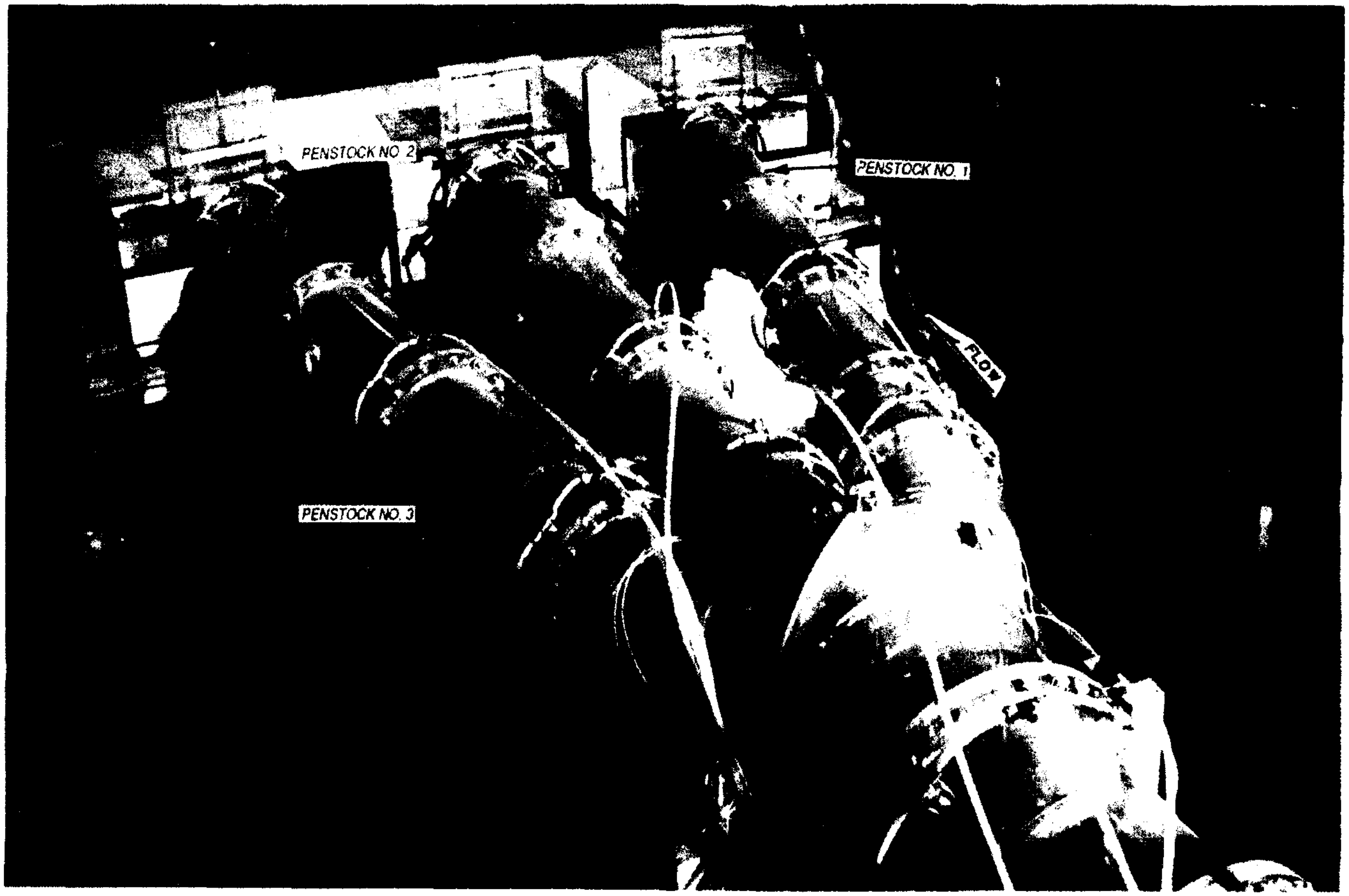


Photo 4. Trifurcation and penstocks, looking downstream

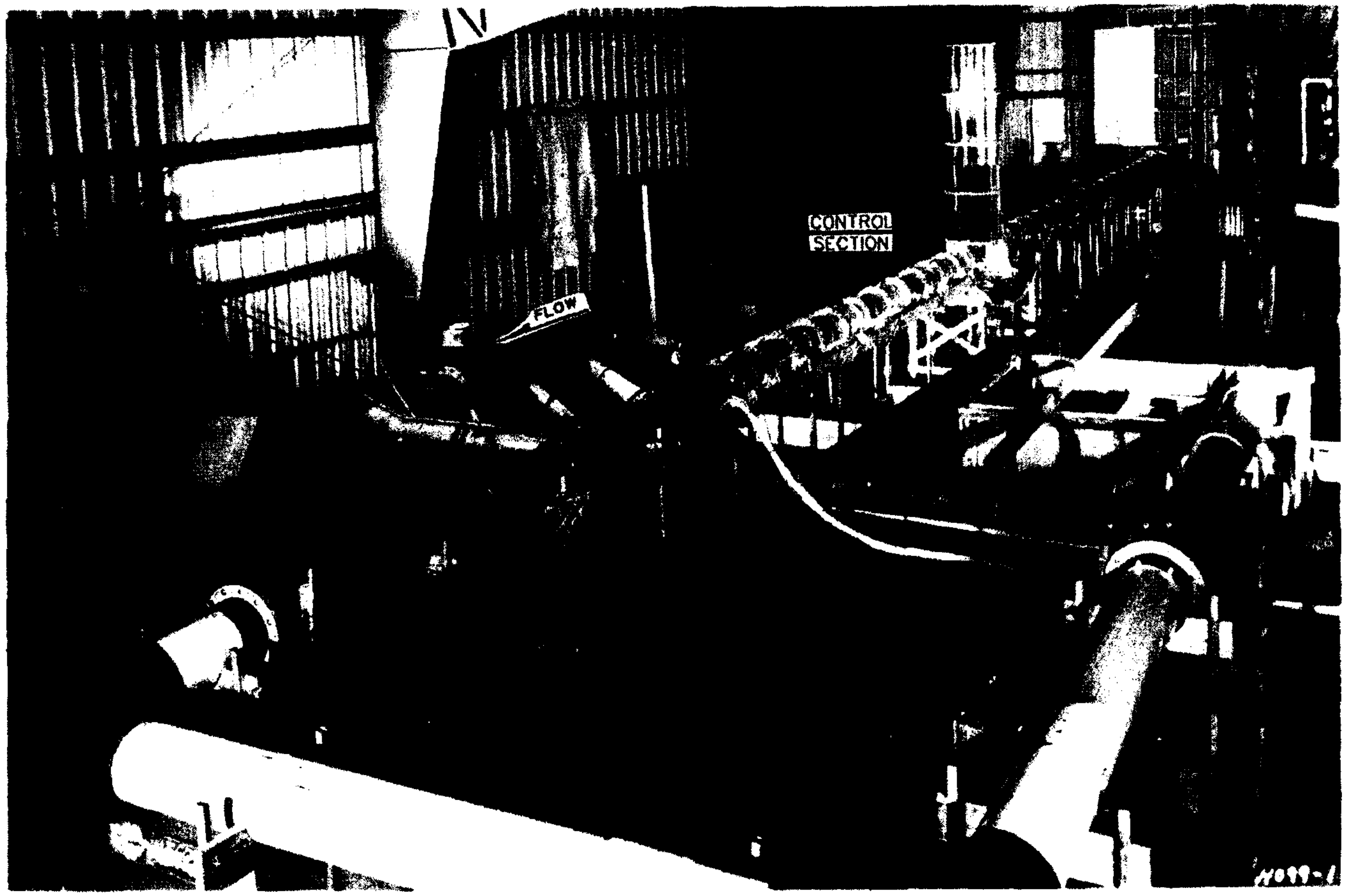


Photo 5. Control section model, looking upstream

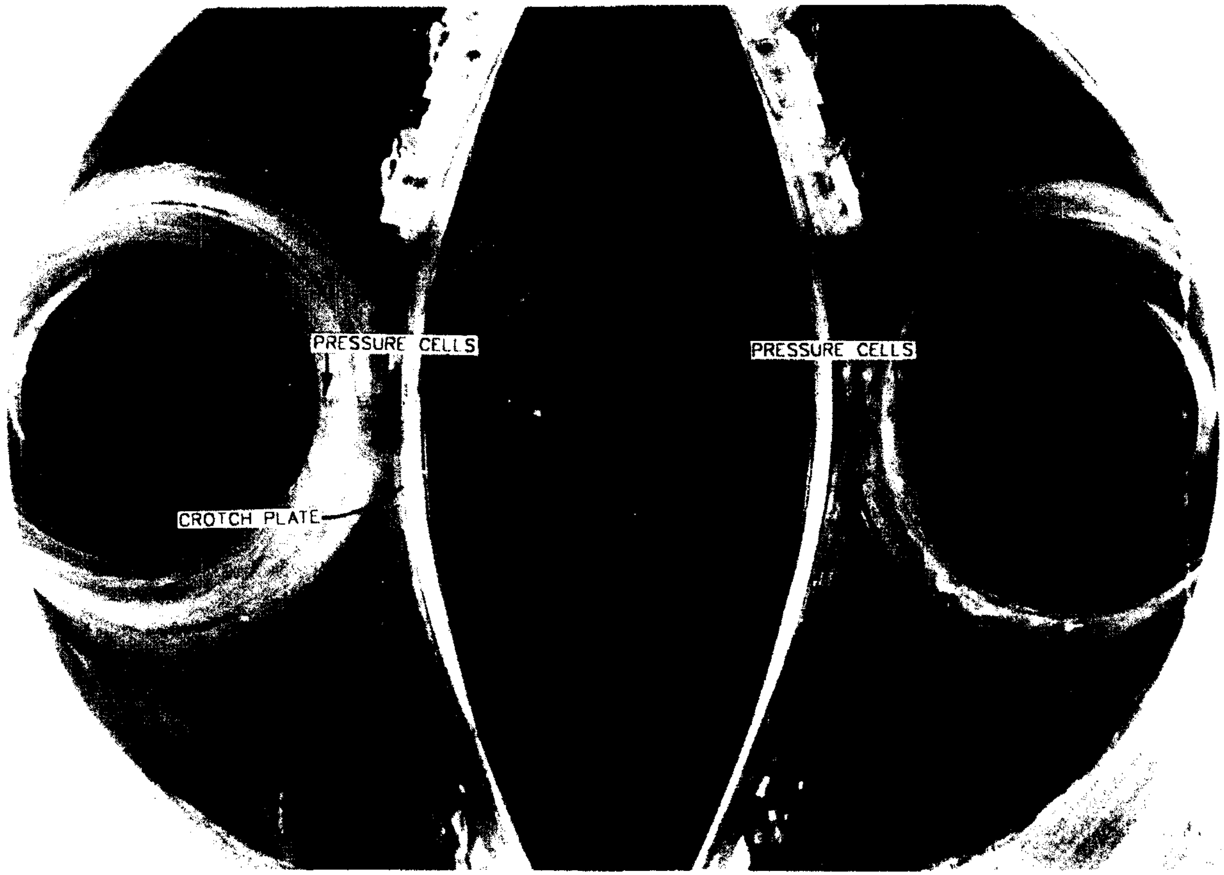
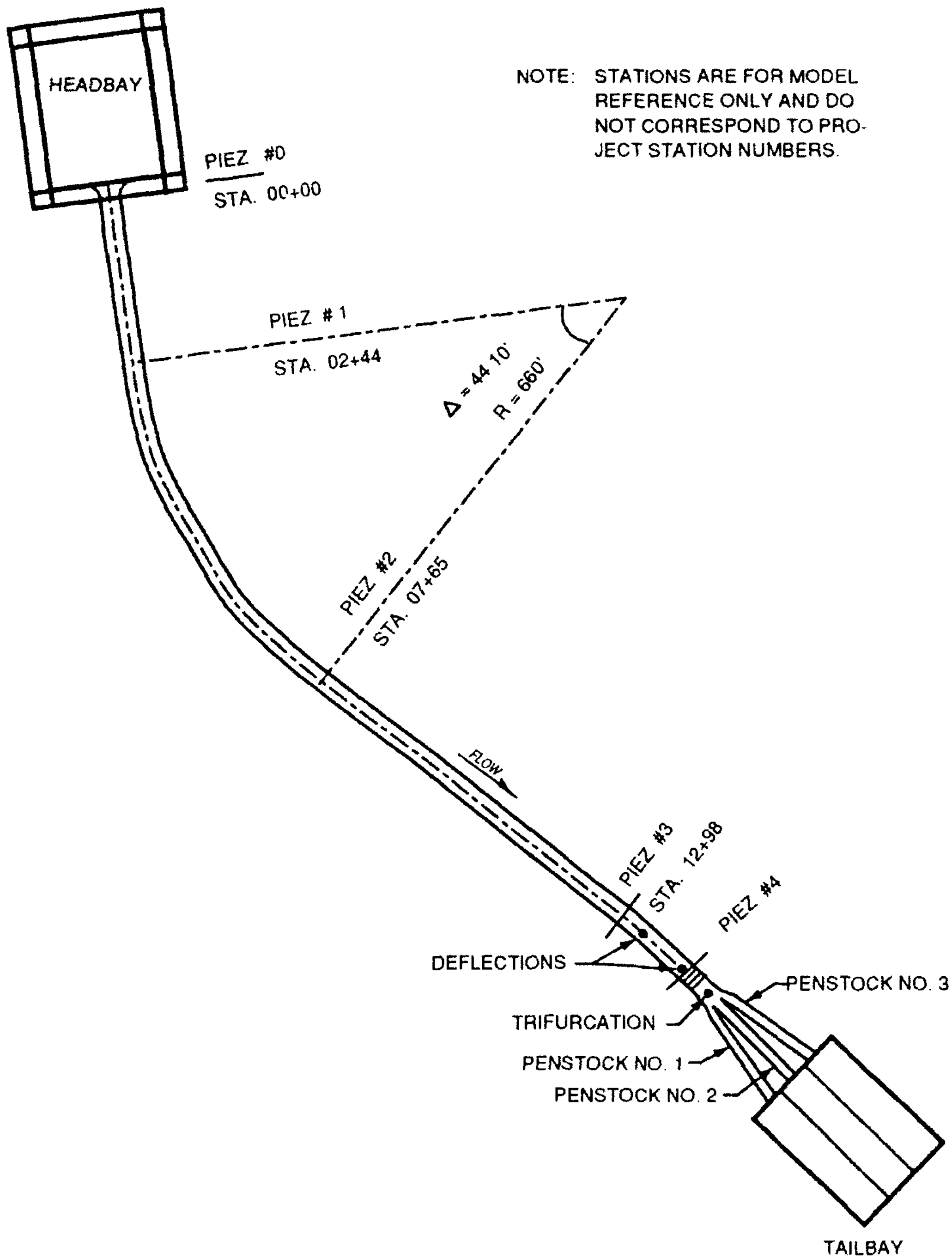
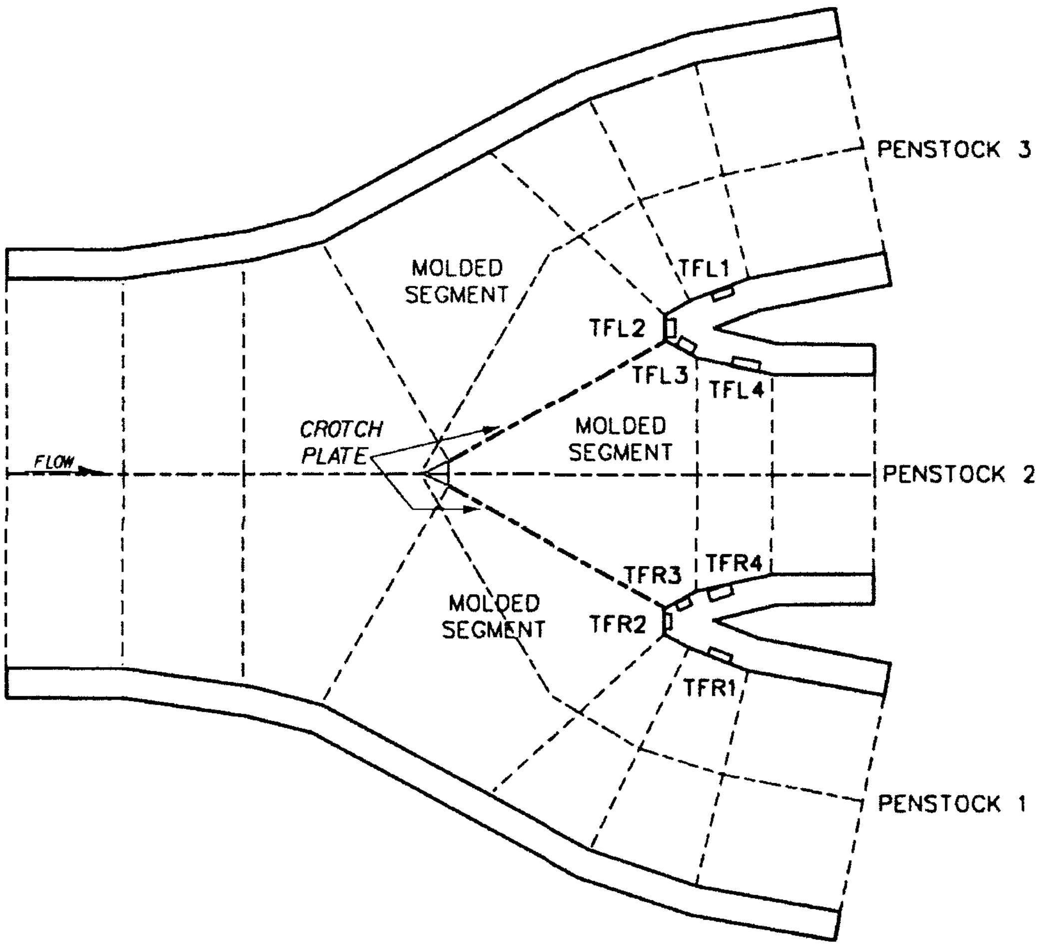


Photo 6. Interior of trifurcation, looking downstream



FORT PECK TRIFURCATION
MODEL LAYOUT

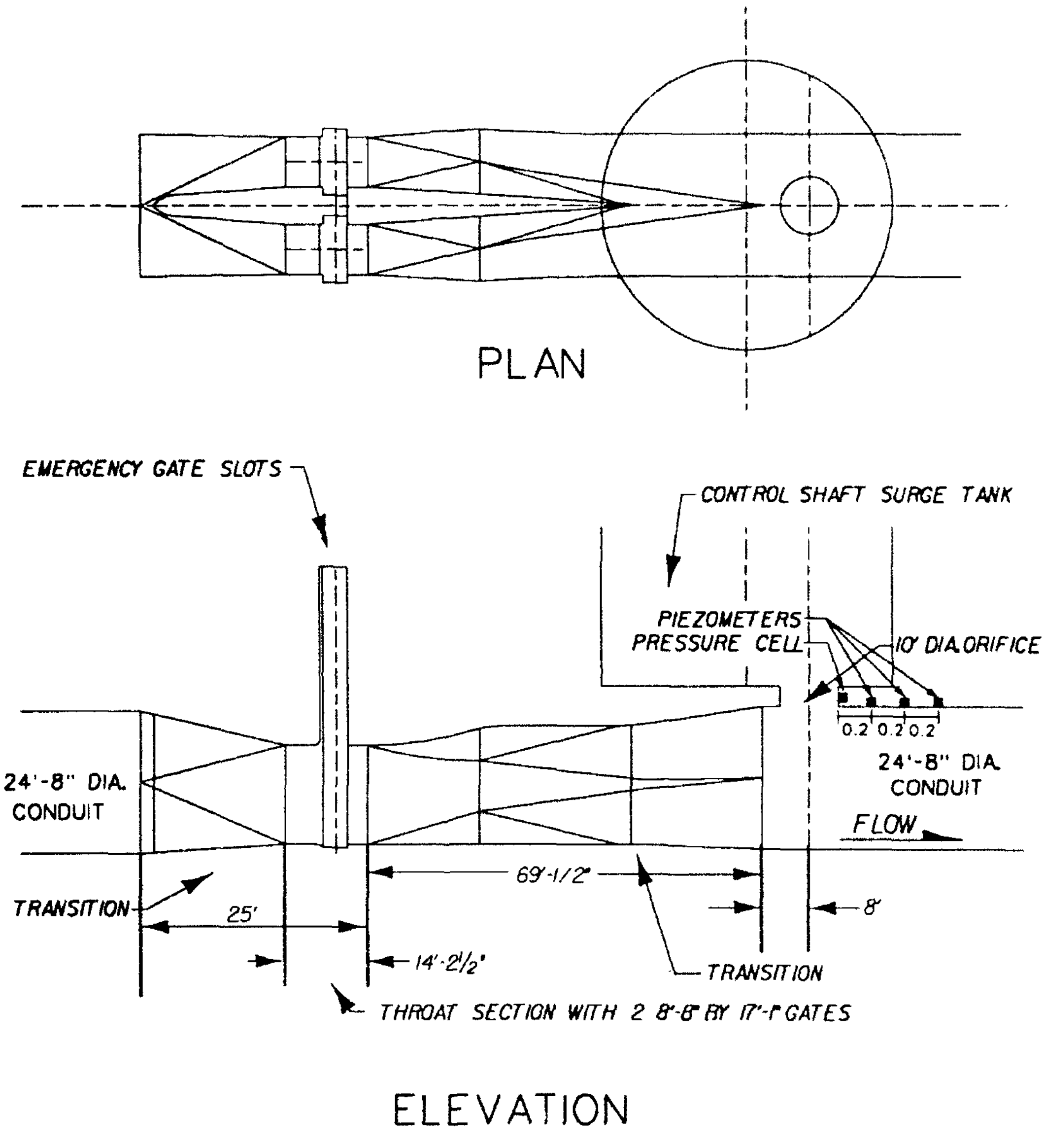


PLAN VIEW

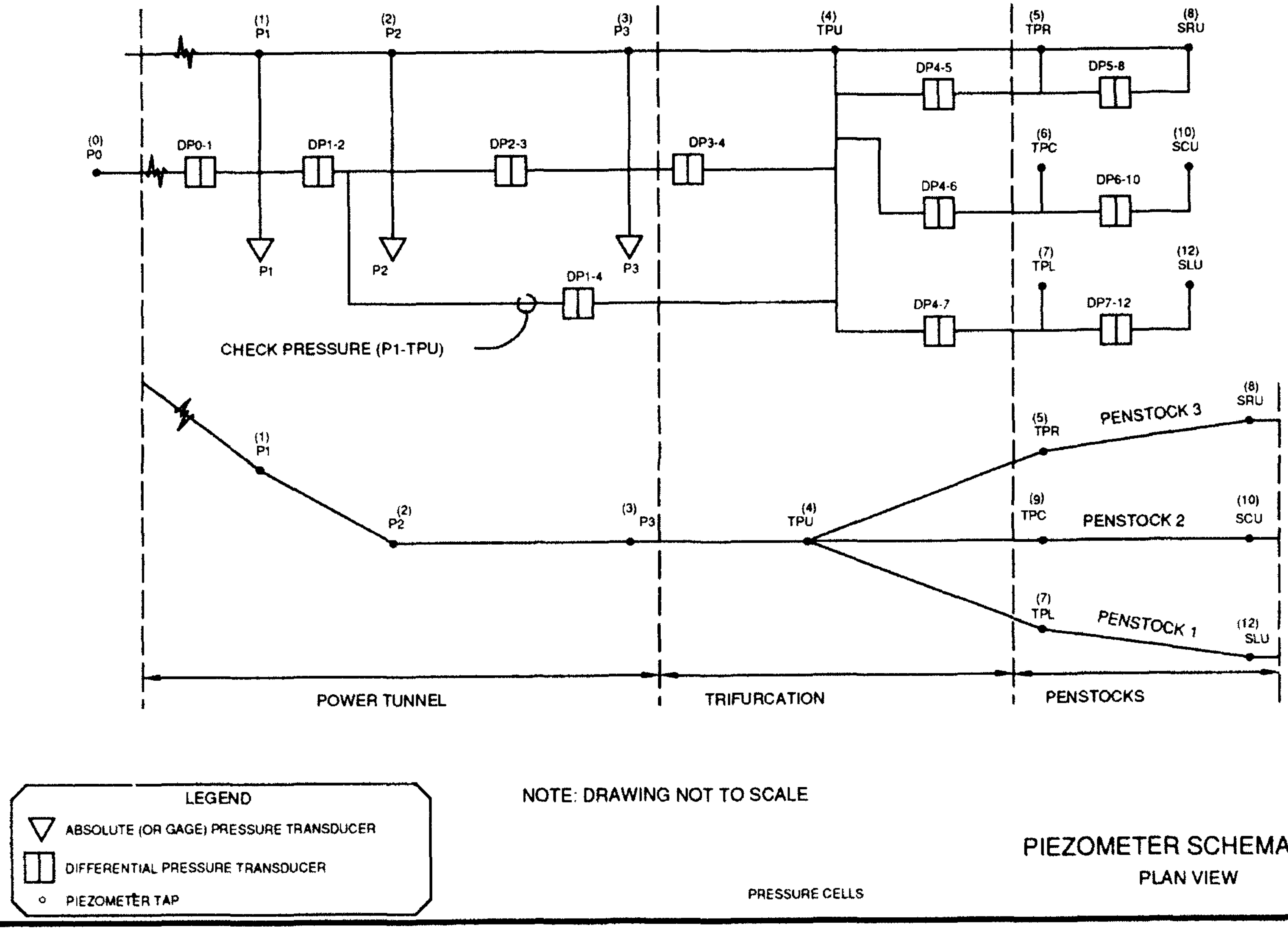
NOTE: REFER TO TABLE FOR DESCRIPTION OF INSTRUMENTATION

PROPOSED FORT PECK TRIFURCATION

PLATE 2

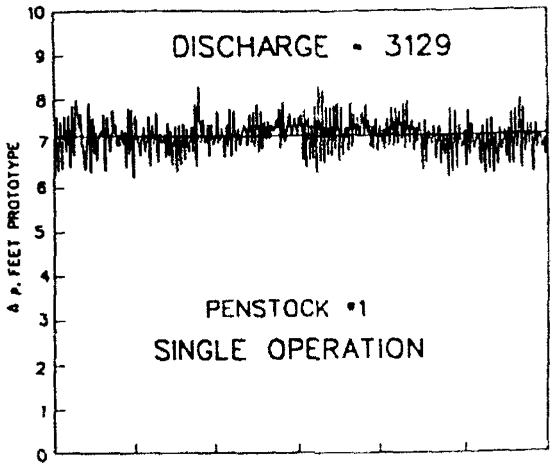


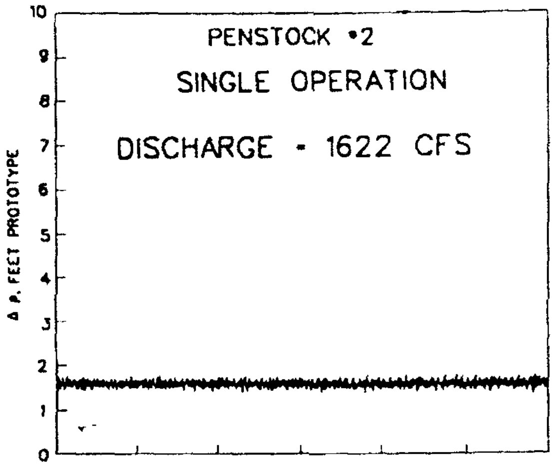
DETAILS OF THE
CONTROL SECTION

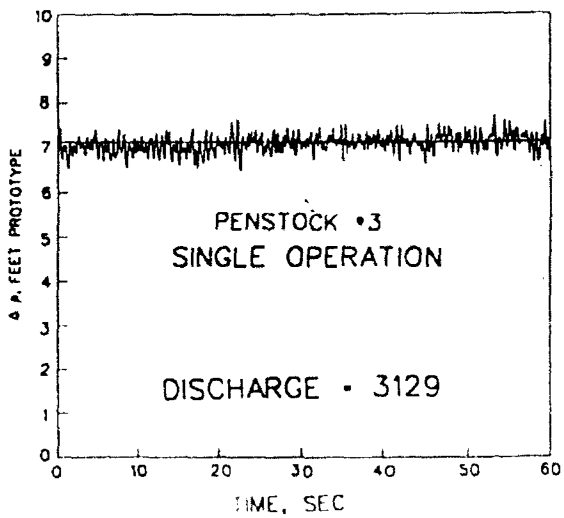


PIEZOMETER SCHEMATIC
PLAN VIEW

PLATE 4

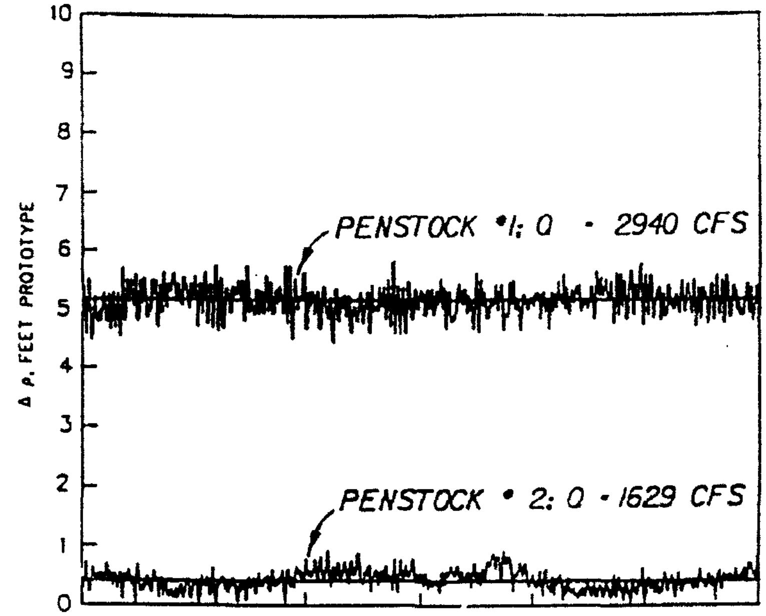




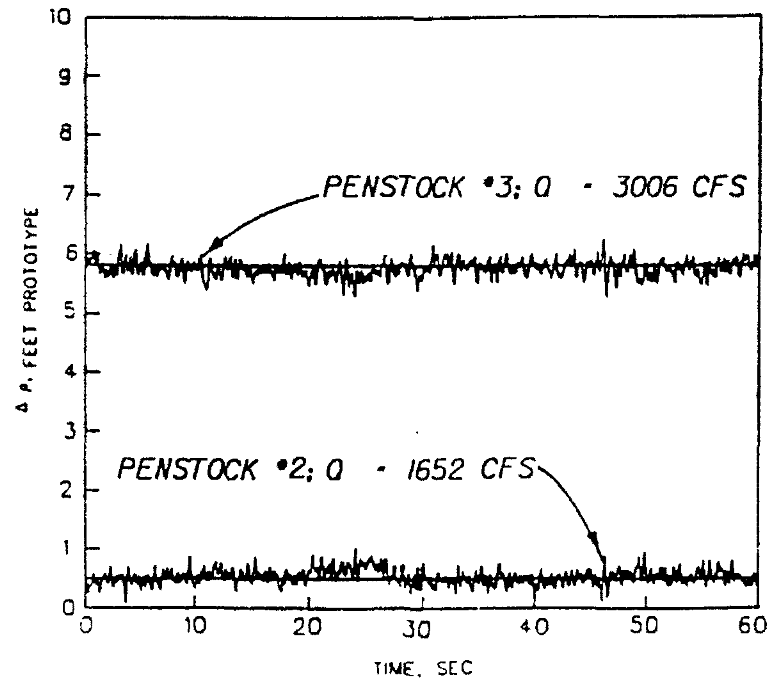


TRIFURCATION DIFFERENTIAL PRESSURE VS TIME

PENSTOCKS 1,2, AND 3, SINGLE OPERATION



PENSTOCKS •1 AND 2

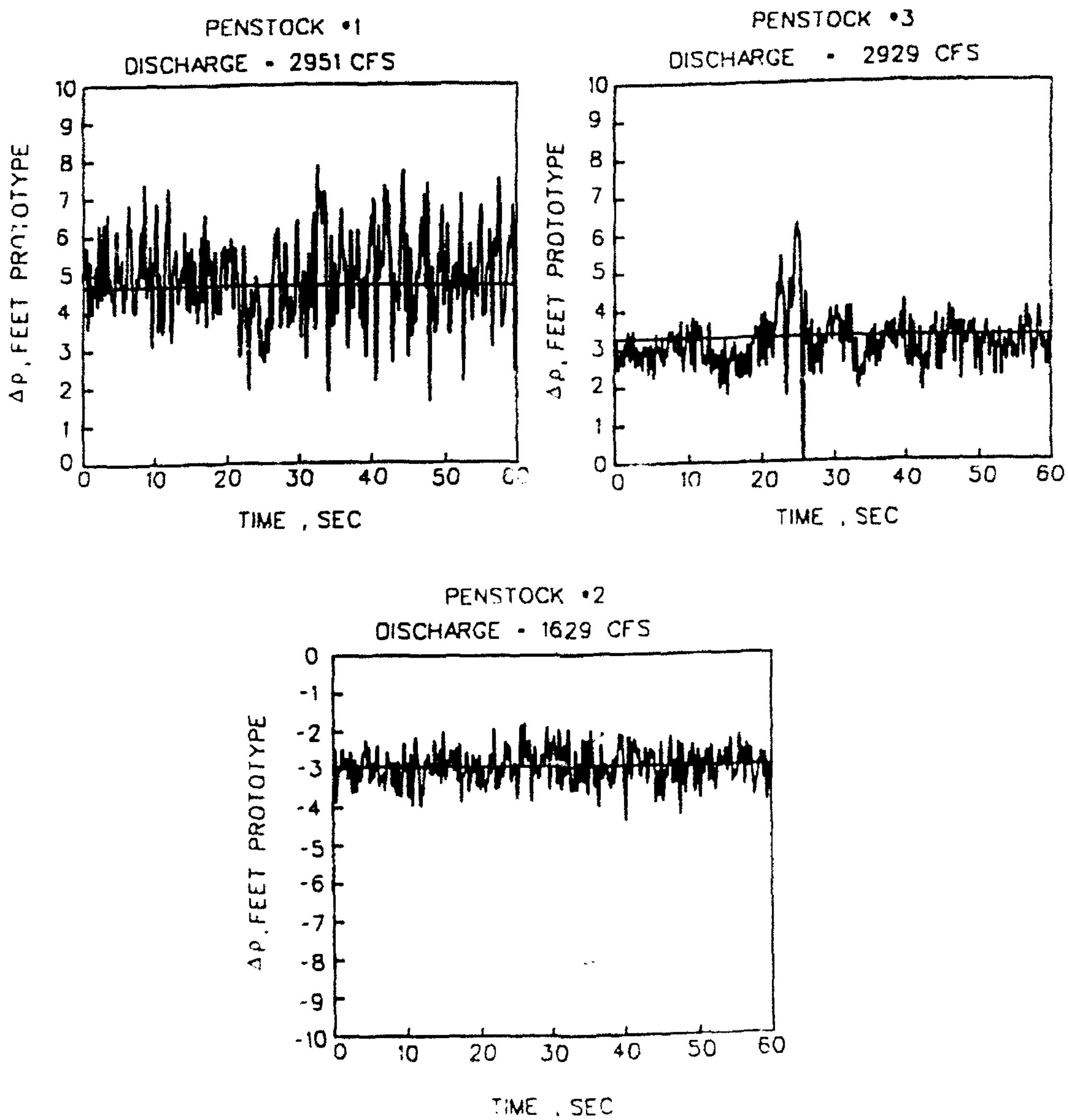


PENSTOCKS •2 AND 3

TRIFURCATION DIFFERENTIAL PRESSURE VS TIME

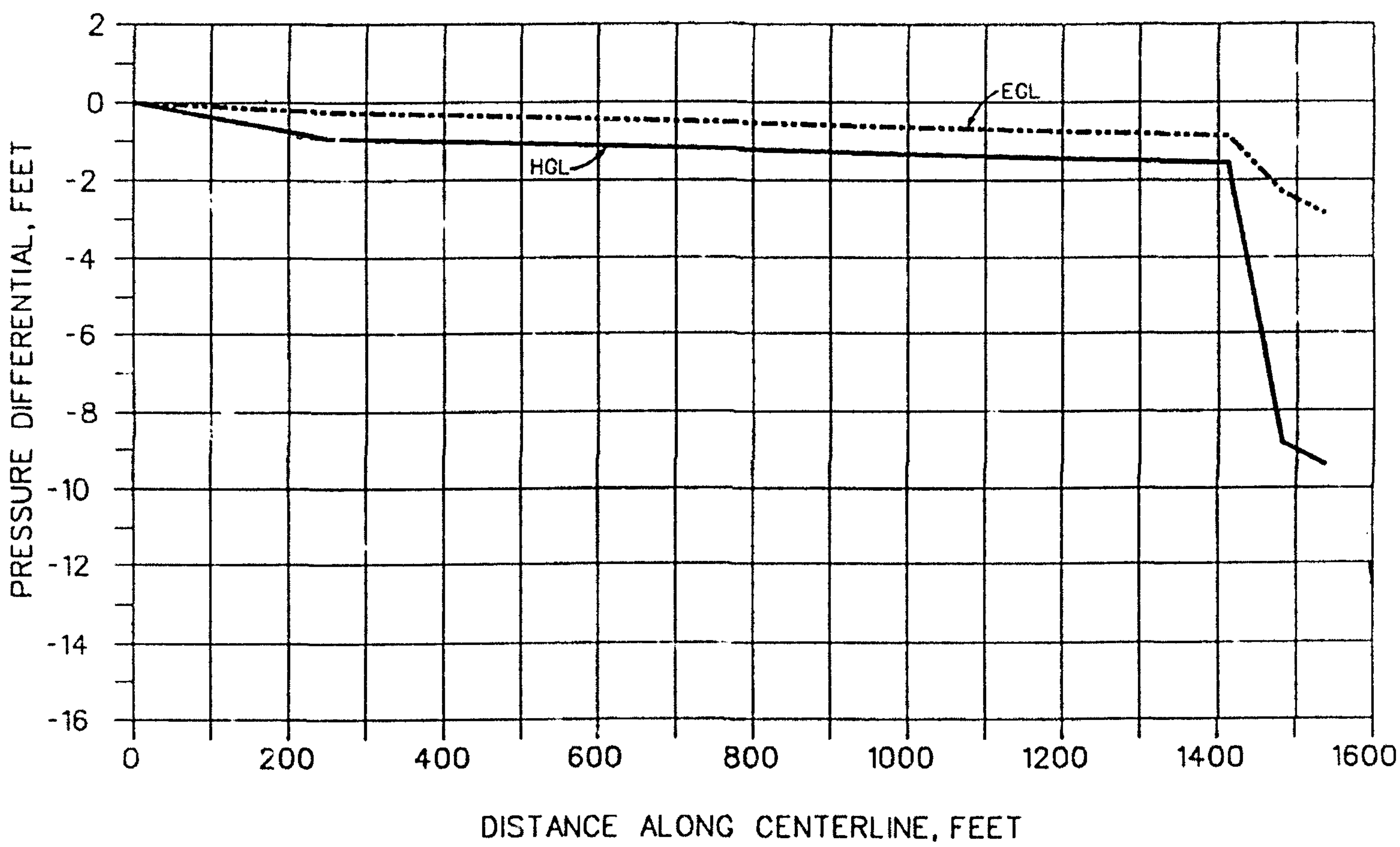
DUAL OPERATION

PLATE 6



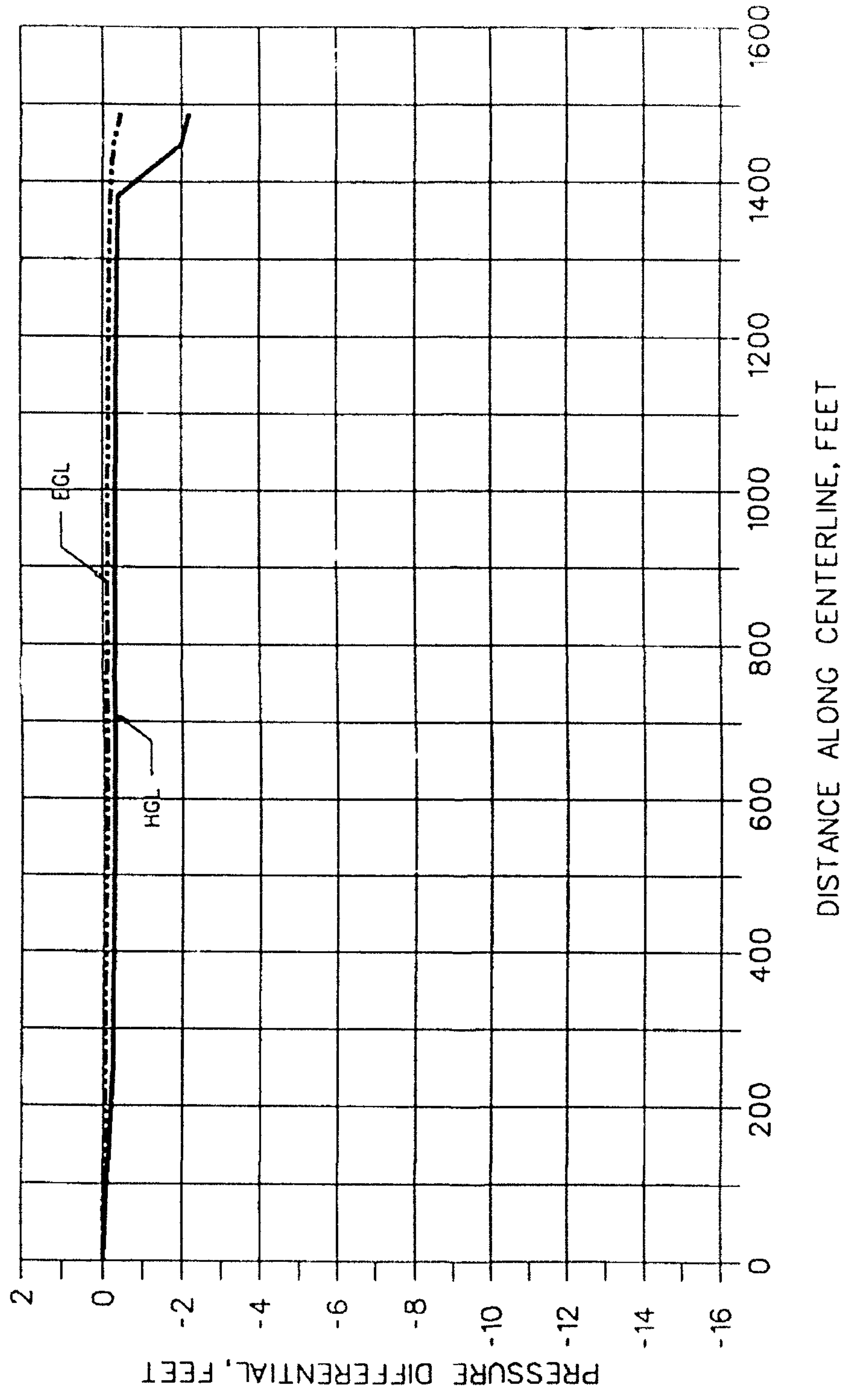
TRIFURCATION DIFFERENTIAL PRESSURE VS TIME

TRIPLE OPERATION

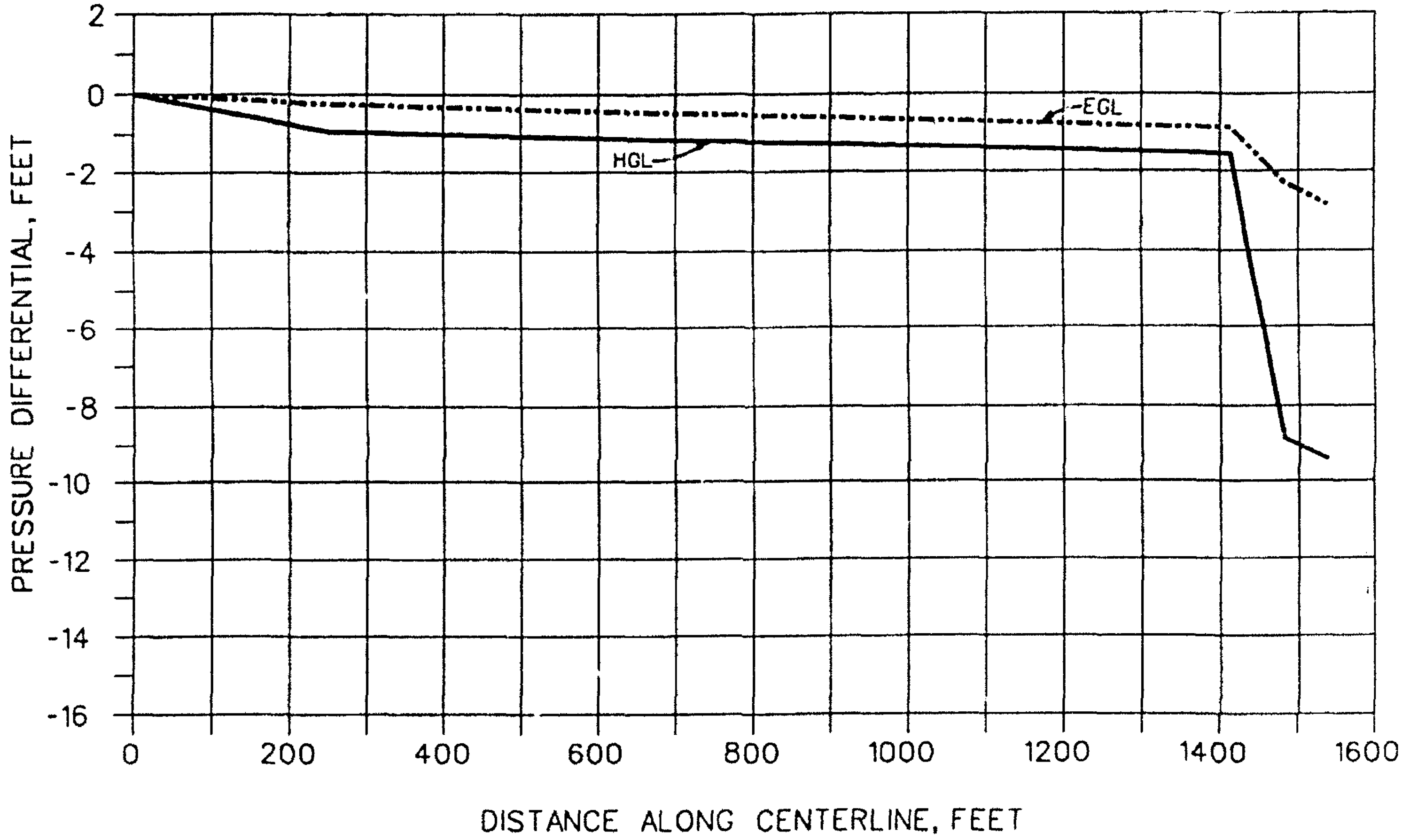


HYDRAULIC AND ENERGY GRADE LINES

PENSTOCK #1, Q = 3129 CFS

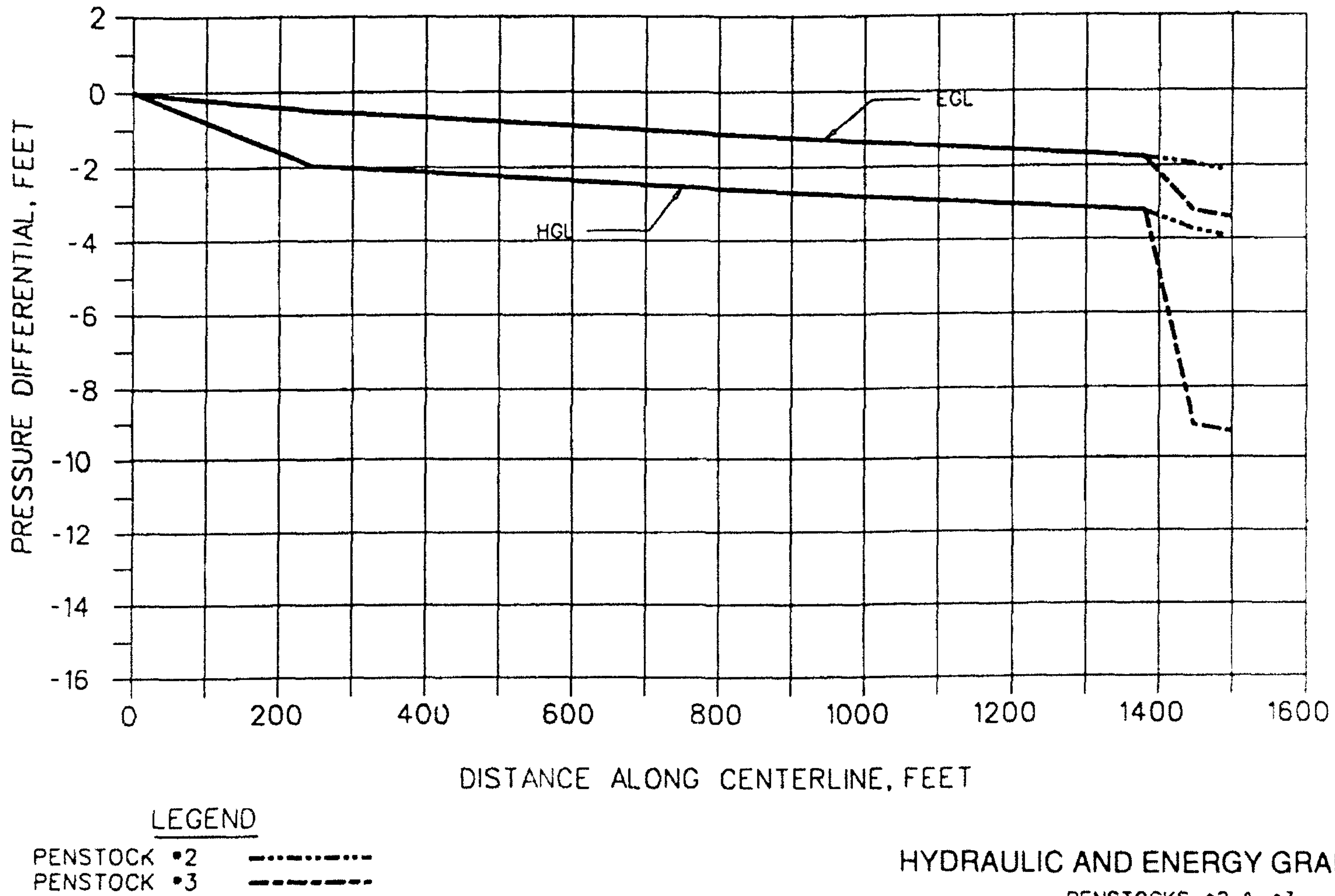


HYDRAULIC AND ENERGY GRADE LINES
PENSTOCK •2, Q • 1622 CFS



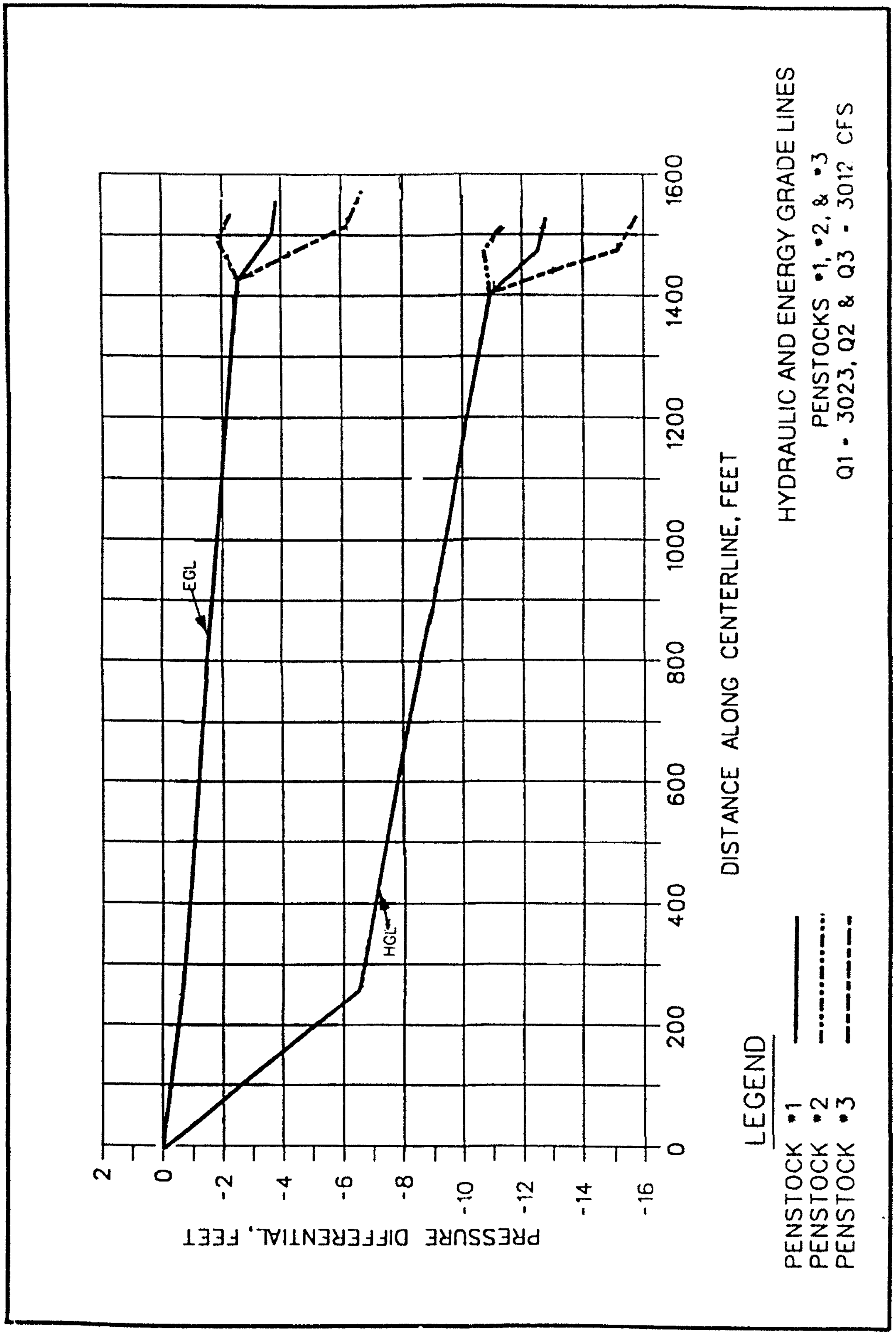
HYDRAULIC AND ENERGY GRADE LINES

PENSTOCK #3, Q = 3129 CFS



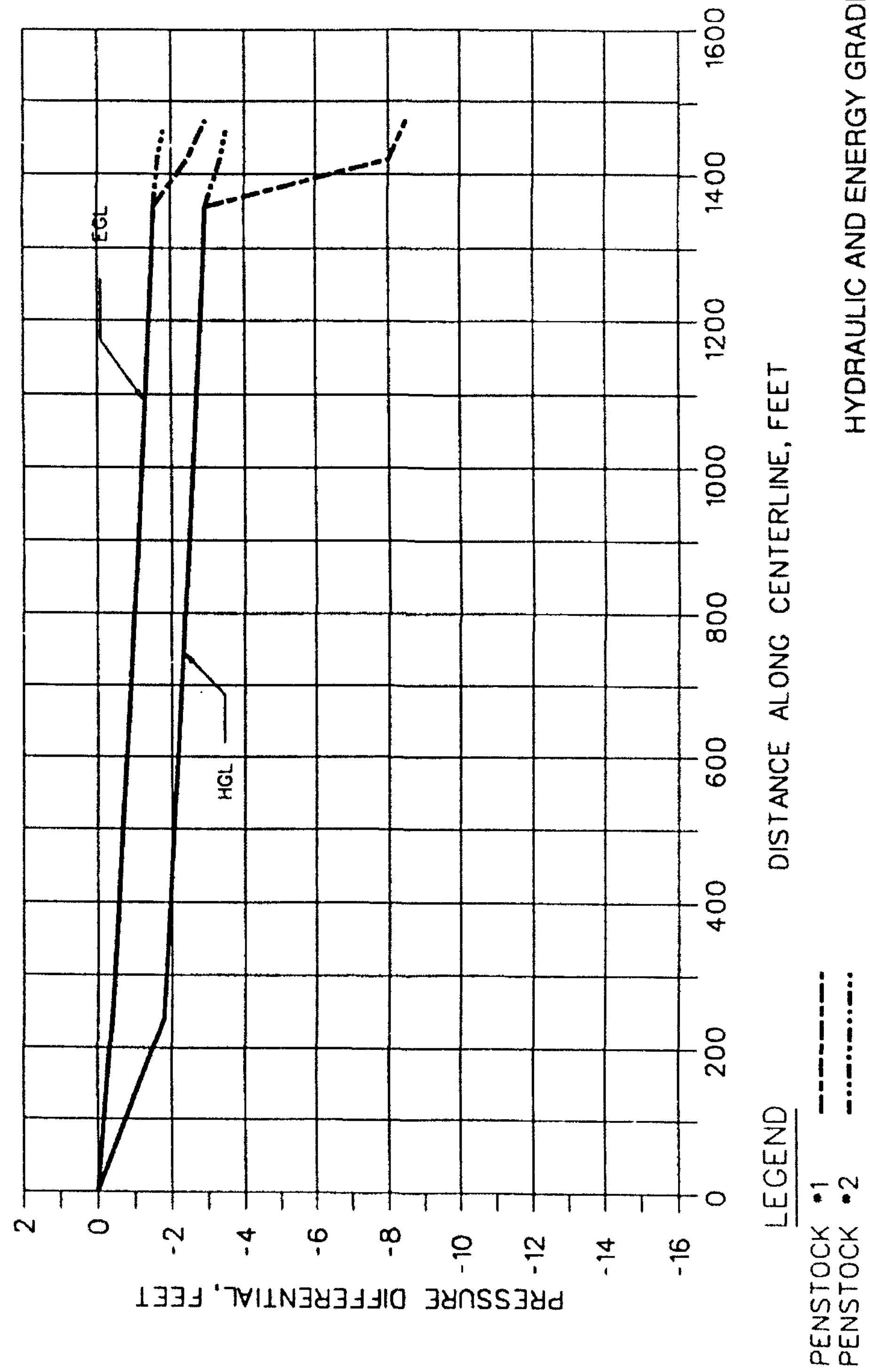
HYDRAULIC AND ENERGY GRADE LINES

PENSTOCKS •2 & •3
Q2 - 1652 & Q3 - 3006 CFS



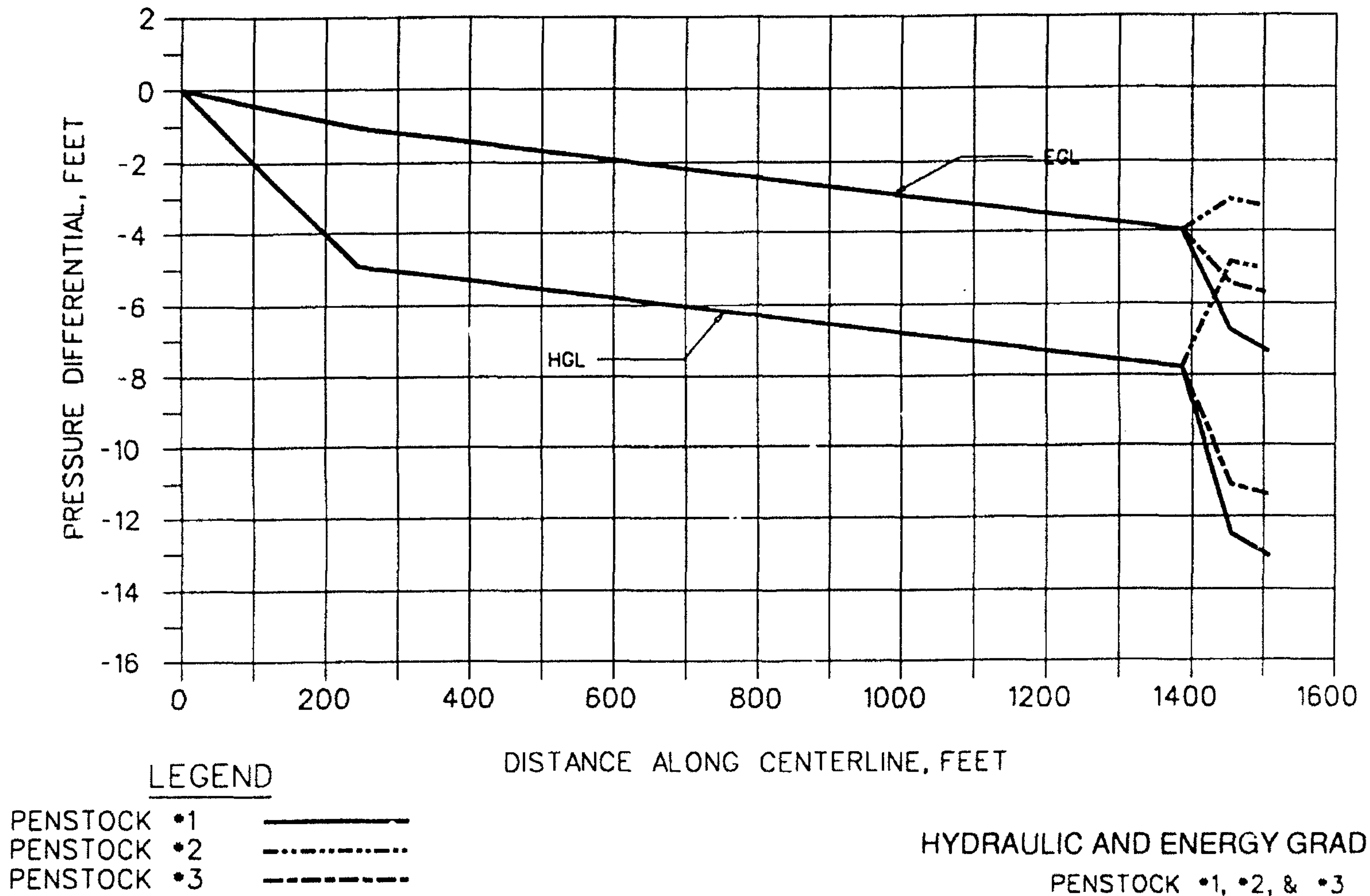
HYDRAULIC AND ENERGY GRADE LINES
PENSTOCKS #1, #2, & #3
Q1 = 3023, Q2 & Q3 = 3012 CFS
PRESSURE DIFFERENTIAL, FEET
DISTANCE ALONG CENTERLINE, FEET
EGL
HGL
2
0
-2
-4
-6
-8
-10
-12
-14
-16
0
200
400
600
800
1000
1200
1400
1600
LEGEND
PENSTOCK #1
PENSTOCK #2
PENSTOCK #3

PLATE 12



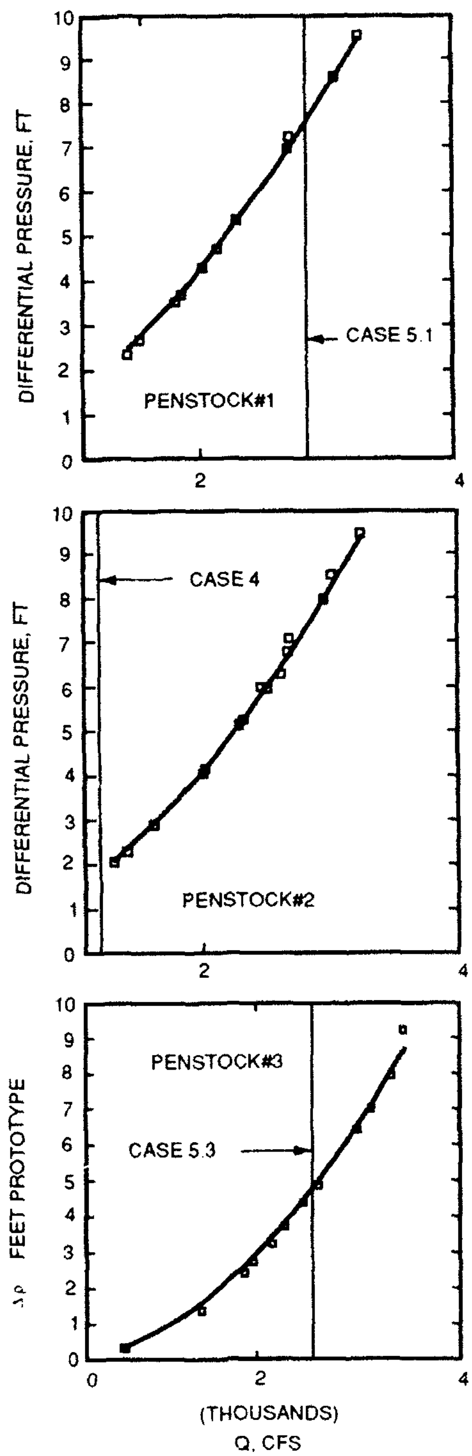
HYDRAULIC AND ENERGY GRADE LINES

PENSTOCKS •1 & •2
Q1 - 2940 & Q2 - 1629 CFS



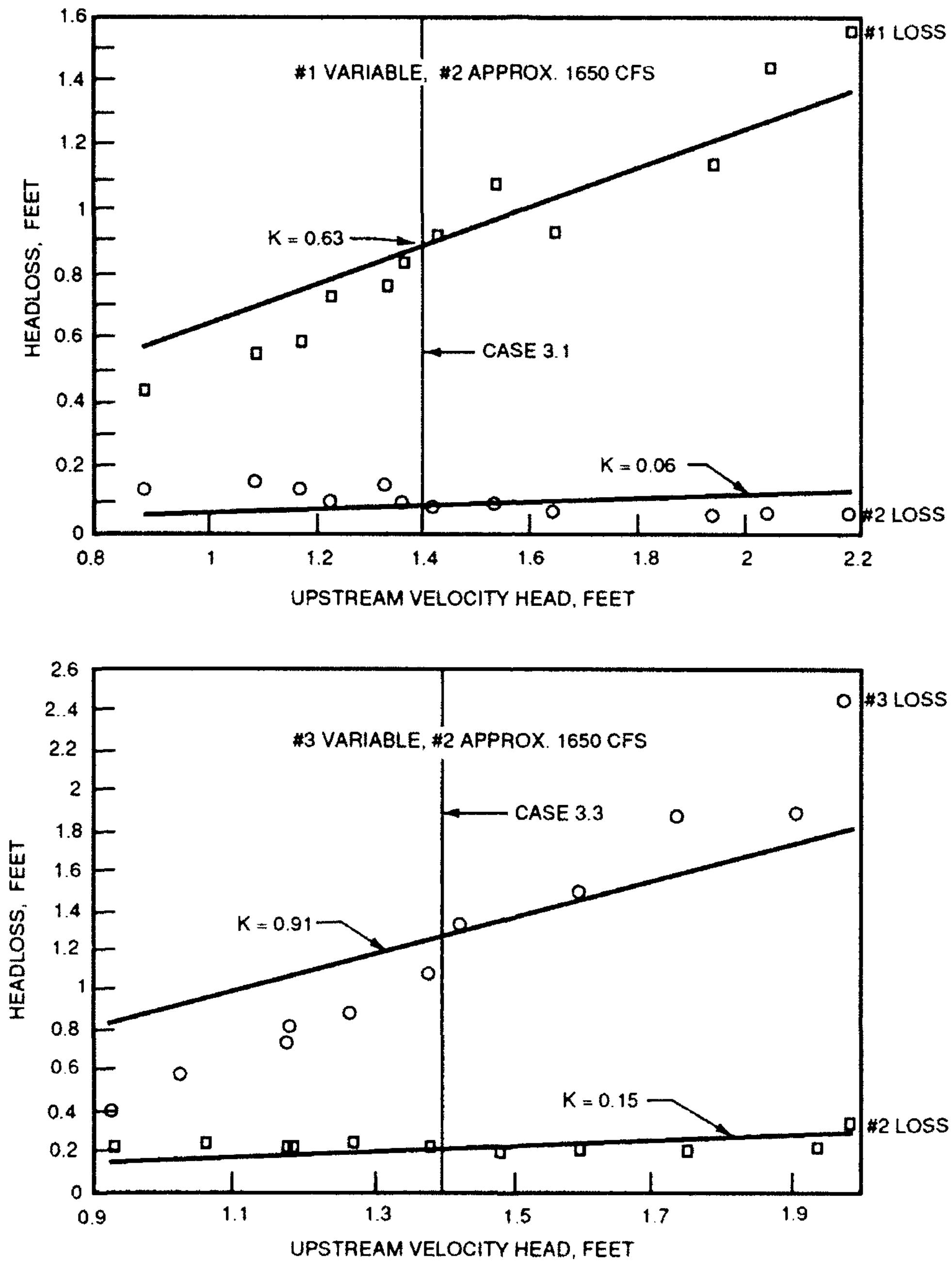
HYDRAULIC AND ENERGY GRADE LINES

PENSTOCK •1, •2, & •3
Q1-2951,Q2-1629, & Q3-2929 CFS



TRIFURCATION DIFFERENTIAL PRESSURE VS. FLOW

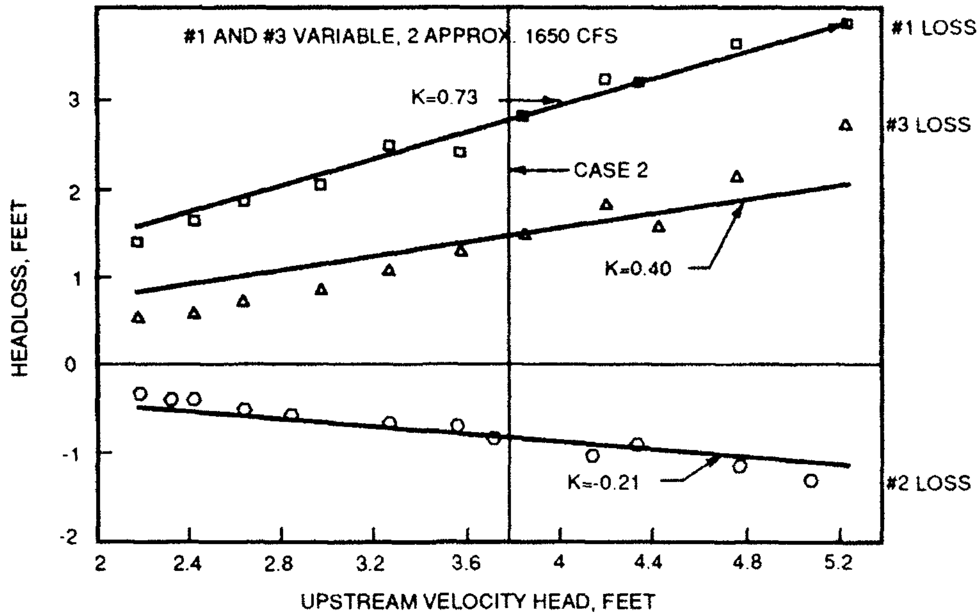
PENSTOCK #1,2,3, SINGLE OPERATION



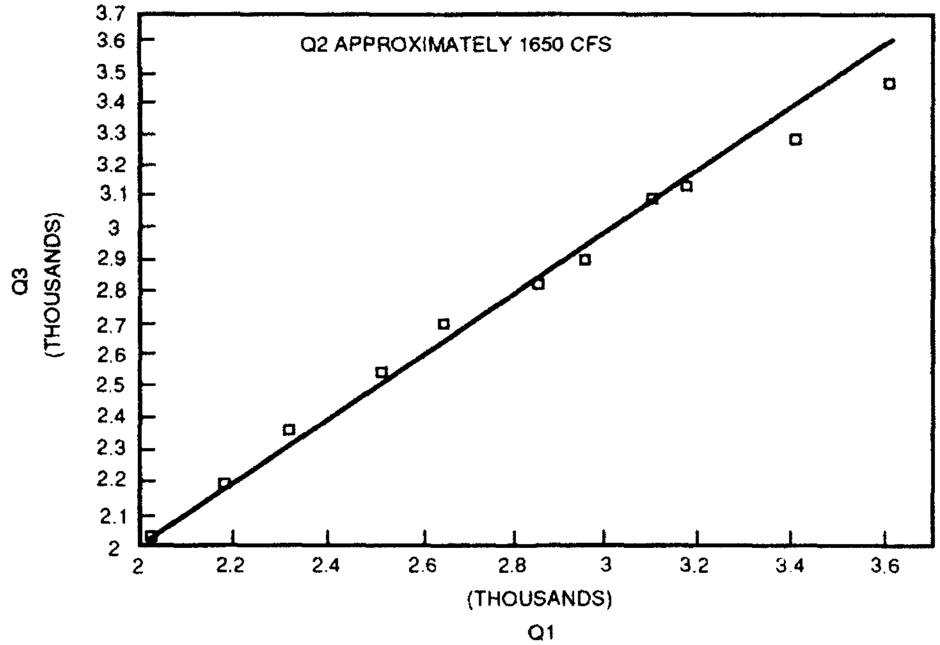
HEADLOSS VERSUS UPSTREAM VELOCITY HEAD

DUAL PENSTOCK OPERATION

PLATE 16



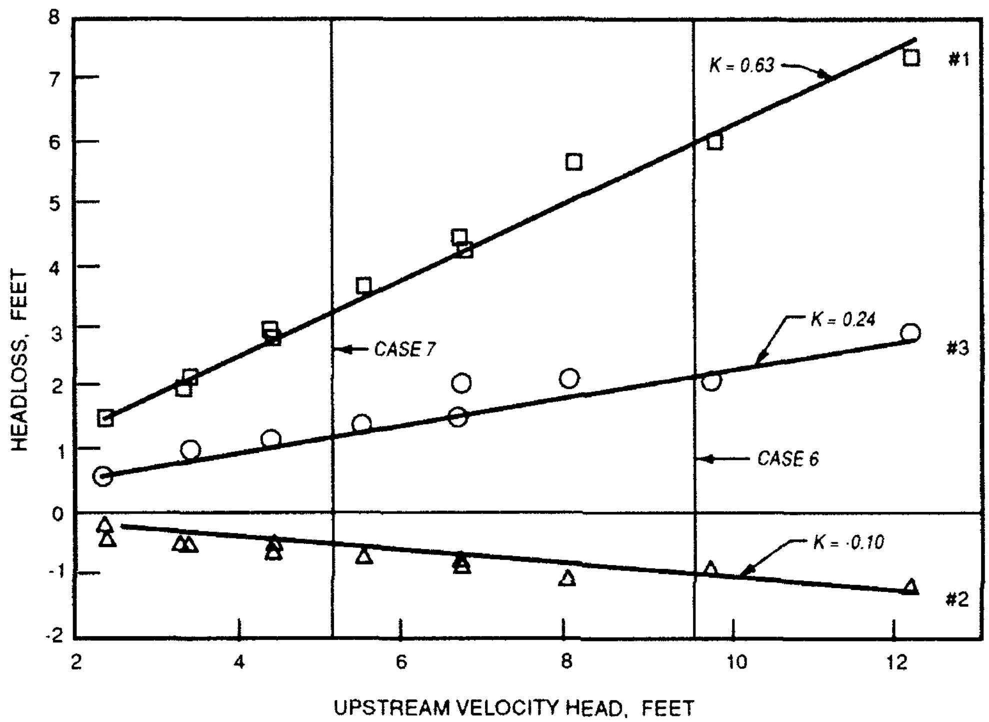
NOTE: CASE 1 UPSTREAM VELOCITY HEAD = 6.2 FEET



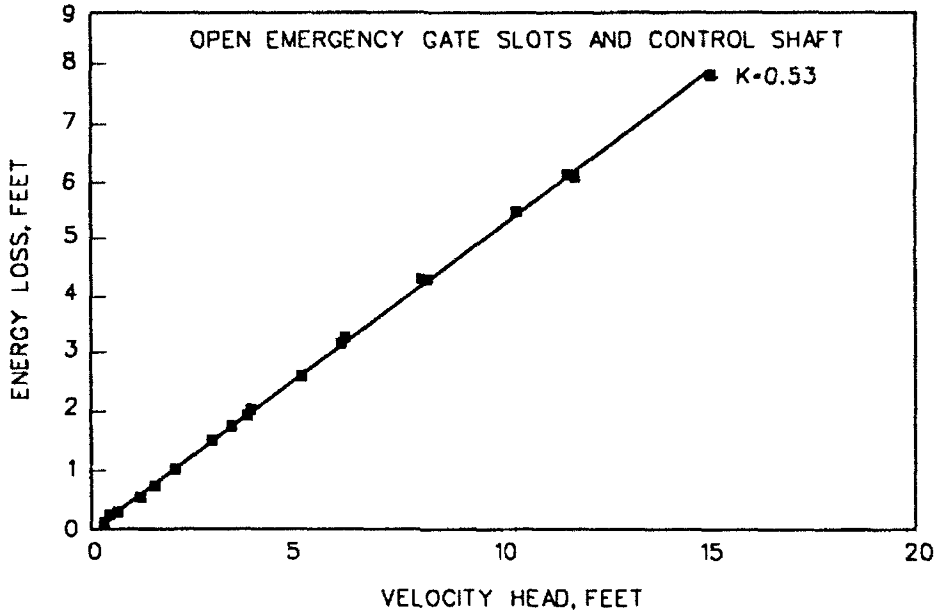
Q1 VS Q3

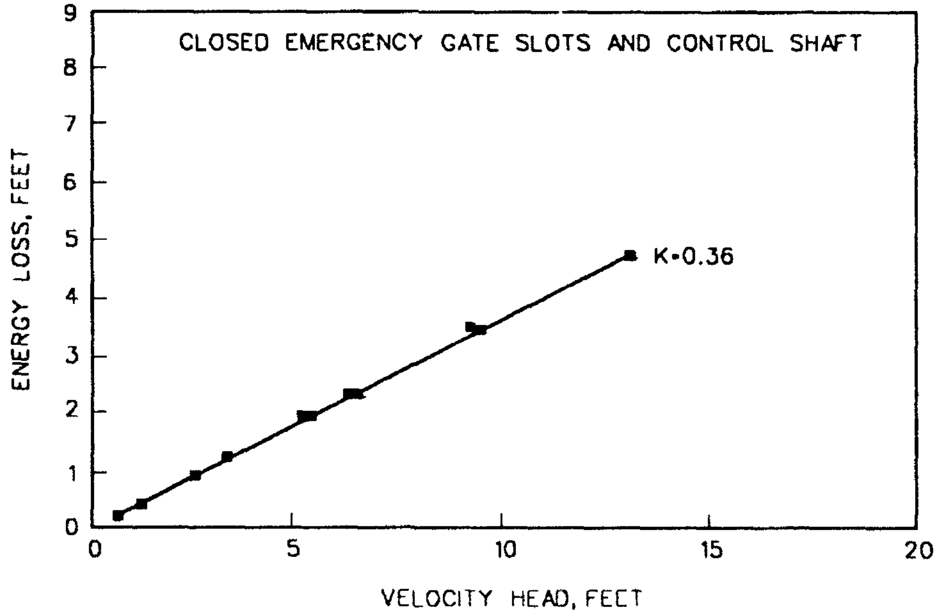
HEADLOSS VERSUS UPSTREAM VELOCITY HEAD

TRIPLE PENSTOCK OPERATION



HEADLOSS VERSUS
UPSTREAM VELOCITY HEAD
PENSTOCKS #1,2, AND 3, WITH EQUAL FLOW

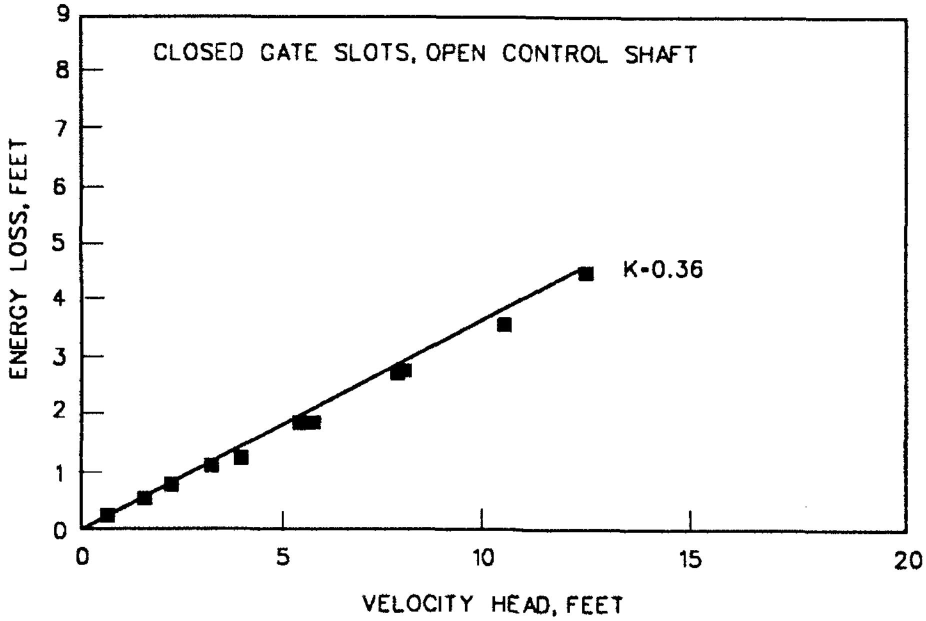


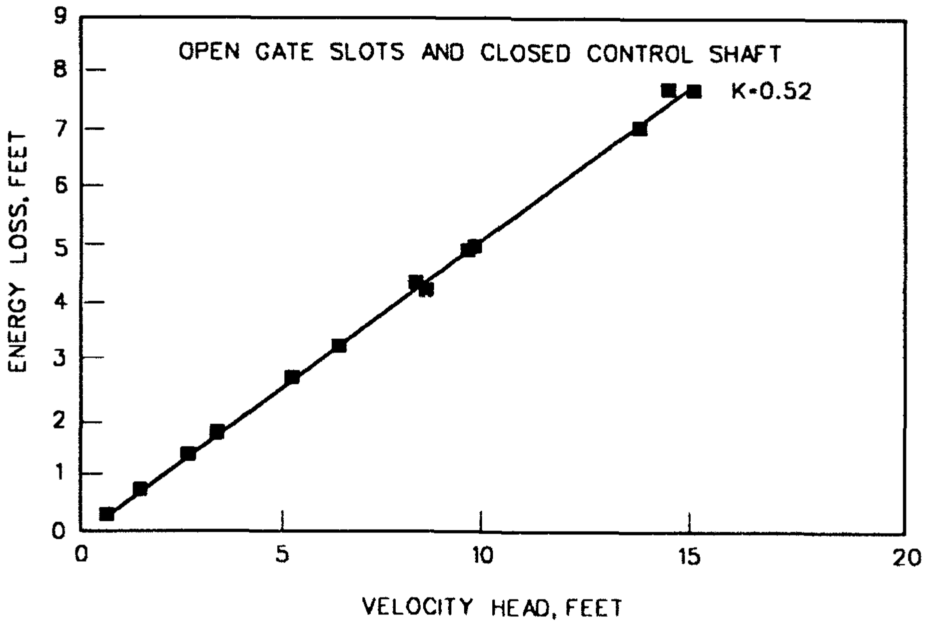


CONTROL SECTION

ENERGY LOSS VS. VELOCITY HEAD

CASE 1 & 2

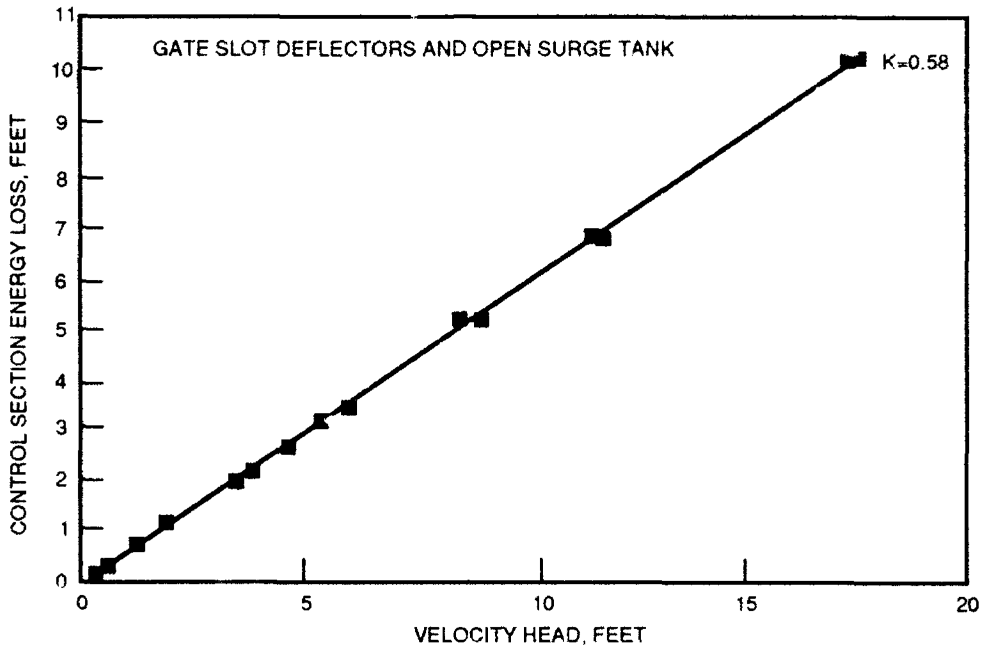


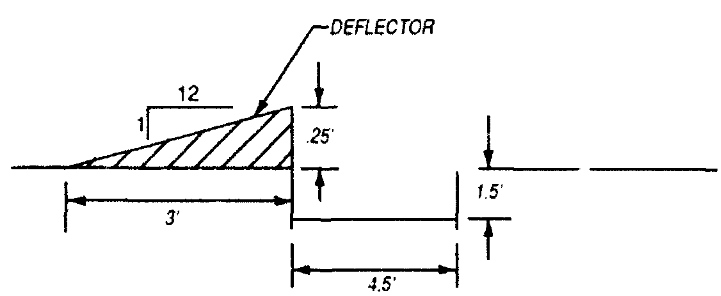


CONTROL SECTION

ENERGY LOSS VS. VELOCITY HEAD

CASE 3 & 4





GATE SLOT WITH DEFLECTOR
PLAN VIEW

CONTROL SECTION
ENERGY LOSS VS VELOCITY HEAD
CASE 5

REPORT DOCUMENTATION PAGE

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13. ABSTRACT *(Maximum 200 words)*
The existing trifurcation and penstock system at Fort Peck Dam, Montana, is reaching the end of its design life and has been determined to have an unacceptable factor of safety. A proposed replacement trifurcation designed by Sulzer Escher Wyss was model tested to determine the flow conditions through the trifurcation and the energy losses associated with various flow combinations. Differential pressures measured across the trifurcation were used with an automated data collection system to determine the losses through the various segments of the trifurcation. Spot pressures were also collected within the trifurcation to determine the stability of the flow fields as they separated to pass through different penstock outlets. The proposed trifurcation was found to be acceptable; however the energy losses were greater than anticipated based on design information. The existing control section located upstream of the trifurcation was studied to determine if simple modifications could reduce energy losses through the control section. The emergency gate slots were determined to cause the highest energy losses through the control section. Filling the emergency gate slots with an insert would significantly reduce the energy loss through the control section.

14. SUBJECT TERMS

Control section energy loss	Sulzer Escher Wyss trifurcation
Energy loss measurement	Trifurcation
Fort Peck Dam	Trifurcation replacement

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